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EVALUATION OF ALTERNATIVE METHODS
FOR WASTEWATER DISINFECTION

THESIS

David C. Piech, Captain, USAF

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Evaluation of Alternative Methods for Wastewater Disinfection

THESIS

Presented to the Faculty of the School of Engineering of the

Air Force institute of Technology

Air University

In Partial Fulfillment of the

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August 1994

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The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

Preface

The purpose of this research was to develop a decision making aid for the selection of an alternative wastewater disinfection method. Impending legislation may restrict or ban the use of chlorine, thus requiring alternative methods to accomplish the disinfection of wastewater.

Existing model equations were manipulated with data obtained from Air Force Wastewater Treatment Plants and existing data from literature. Due to the variability of WWTPs, this document is intended to serve as a preliminary decision making guide only. Pilot studies must be performed before any final decisions are made with respect to selecting a wastewater disinfection method. The model equation manipulations give promise that ultraviolet disinfection systems are well suited to Air Force WWTPs. Further research should be conducted in the area of developing a computer based decision making aid.

In accomplishing the manipulations and writing of this thesis, I have had tremendous help and support from others. I would especially like to thank my faculty advisor, Dr. Charles Bleckmann, for his patience, assistance, and motivation. I also wish to thank Dr. Panos Kokoropoulos, my reader for his knowledgeable insight in the area of disinfection and data representation. Finally, a word of thanks to my understanding and loyal pal, Mongo, for those long days and nights when he was unintentionally ignored.

David C. Piech

Table of Contents

List of Figures

Page

List of Tables

AFIT/GEE/ENV/94S-18

Abstract

This study investigated the alternative methods of wastewater disinfection. Areas of interest included methods of operation, ease of maintenance, and effectiveness for various types of wastewater. A literature search revealed three major disinfection options, which include: chlorination/dechlorination, ultraviolet light, and ozone. A questionnaire was sent to the active duty Air Force installations that operate wastewater treatment plants, requesting permit limitations and monthly averages for a variety of wastewater parameters. The majority of Air Force wastewater treatment plants use chlorine for disinfection. Using the data obtained from the questionnaire responses and established wastewater parameters from other research, the basic design model equations were manipulated. The results showed that ultraviolet and ozone disinfection are safe alternatives to chlorine, however, ultraviolet systems appear to be better suited for the size and type of wastewater treatment plant that is typical of an Air Force installation.

Evaluation of Alternative Methods for Wastewater Disinfection

I. Introduction

Background

With increased awareness of the necessity for a sustainable ecological future, governments and citizens around the world are focusing more closely on protecting and preserving the environment. Important among these issues is the quality of effluents which wastewater treatment plants discharge into lakes and rivers.

Federal Water Pollution Control Law, more commonly referred to as the Clean Water Act (CWA) requires that the discharge of pollutants to waterways of the U.S. be controlled or prevented. Prior to 1970, there was no effective program to directly enforce environmentally oriented limits on the discharge of pollutants to water, despite the federal/state program to protect surface water. (Arbuckle, 1993:152). In 1972, Public Law 92-500, The Federal Water Pollution Control Act (FWPCA), was enacted and made the Environmental Protection Agency (EPA) responsible for setting nationwide effluent standards. Today, the Clean Water Act (CWA), Public Law 95-217, is perhaps the most tested, most innovative and most enforceable of our federal environmental statutes (Arbuckle, 1993:154).

The objective of the CWA is to "restore and maintain the chemical, physical and biological integrity of the nation's waters." In order to achieve this objective, the act establishes national goals which are:

- achievement of a level of water quality which provides for the protection and propagation of fish, shellfish and wildlife and for recreation in and on the water

- elimination of the discharge of pollutants into surface waters

- the discharge of toxic pollutants in toxic amounts be prohibited. (Arbuckle, 1993:155)

Wastewater treatment plants must comply with the requirements of the CWA or the laws of the state. Permits must be obtained and abided by to include strict monitoring of the effluents produced by the plants.

General Issue

During the 1970's reports of fish kills, seemingly healthy streams devoid of life, and identification of harmful chlorination byproducts prompted investigations by the Environmental Protection Agency (EPA). The EPA reported in 1976 that some fish and fish food organisms tend to be more sensitive to chlorine than other freshwater animals (WPCF, 1984:3). However, since chlorine is so effective and the most economical disinfection method, the majority of WWTPs still use it today.

Wastewater effluents must be disinfected to decrease the disease risks associated with the discharge of wastewaters containing human pathogens into receiving waters. The disinfection process, through the destruction of pathogenic agents, provides a barrier to possible waterborne disease before the wastewater is released to the environment (Stover, 1981:1637). Otherwise, these pathogens will threaten the quality of domestic drinking water supplies, water-contact recreational waters, and shellfish growing areas (WPCF, 1990:820). Disinfection with chlorine has been and is still the most popular choice to accomplish disinfection.

The standards established for disinfection of wastewater treatment vary throughout the states. "The standards are generally dependent on the water quality standards for the receiving waters, and, in some instances, have been applied on a seasonal basis" (Stover, 1981:1637). Typically, the standards establish limits for total and fecal coliforms expressed as the mean probable number (MPN) per 100 milliliters (ml) (MPN/100ml). For example, the California standard for nonrestricted recreational use of wastewater specifies a 7-day median total coliform of 2.2/100ml or less (Stover, 1981:1637).

Recently, the Environmental Protection Agency proposed developing a plan for reducing or prohibiting the discharge of chlorine and chlorinated compounds into bodies of water. Millions of tons of chlorine are used in the United States each year, principally in manufacturing plastics, paper, and industrial solvents (Cushman, 1994:5). Although chlorine is widely used to treat drinking water, environmentalists have focused their concerns about health effects on wastewater discharges which end up in the food chain through fish and other animals (Noah, 1994:7). Under proposals from the Clinton administration, a task force to examine the health effects of chlorine and chlorinated compounds would be convened within six months after a revised clean-water bill is passed. The study will include an examination of the impact of the chemicals on wildlife (Cushman, 1994:5). After reviewing the task force's study, the EPA administrator should consider any number of appropriate actions, including restricting or prohibiting use of chlorine and chlorinated compounds. Under the proposal, the EPA administrator would be required to make this decision within 30 months of the clean-water bill's passage.

Specific Problem

The Air Force owns and operates permitted wastewater treatment plants at several of its installations, see Appendix A. They must comply with specific discharger requirements. If the use of chlorine as a disinfection method is either banned or restricted, the Air Force will be forced to seek alternative methods of disinfecting the effluent from the WWTPs.

Objectives

With the impending stricter regulations on the use and discharge of chlorine, this research will serve as a starting point for selecting and implementing alternative methods of wastewater disinfection. The aim of this research is to:

- review the current state of knowledge on the advantages and disadvantages of various methods of wastewater disinfection and their potential effects on the environment and public health.

- survey the Air Force WWTPs for the methods of disinfection currently in operation

- develop a decision making document to aid Air Force decision makers in making a preliminary selection of an alternative to the use of chlorine for disinfection.

Scope and Limitations of Research

This research will only include information obtained from WWTPs operated by the Air Force in the continental United States and Alaska. The alternatives reviewed will include chlorination/dechlorination, ozone, and ultraviolet light, since these alternatives are the most widely employed at WWTPs in the U.S. Cost data was obtained directly from manufacturers, operators, and standard wage rates as employed by the Air Force.

Thesis Overview

Chapter I presents the legislation that governs the operation of WWTPs and the proposed regulations as they stand at the time of this writing. This chapter also identifies the specific problem, research objectives, scope and limitation of the research. Chapter II provides background information gleaned from literature on the developments, trials, and effectiveness of the alternative methods of disinfecting effluent from WWTPs. Chapter III presents the methodology for choosing an alternative method of disinfection. Chapter IV presents the results of the research efforts and documents the survey information. Chapter V presents the conclusions from the study, and makes recommendations for future research efforts.

II. Review of Literature

Overview

This chapter reviews the literature concerning the disinfection of effluent from WWTPs and the alternatives to using chlorination. The chapter is divided into two parts. The first part describes the need for disinfection, the process of disinfection, and the methods, means and mechanisms of disinfection. The second part of this chapter examines the alternatives to chlorination.

Disinfection

The disinfection of wastewater is not a new practice. More than a century ago, chlorine and its compounds were applied directly to wastewater to control odors, which were then believed to cause disease. More recently, concern has focused on the effects wastewater discharges have on drinking water supplies, shellfish areas, and on bathing and water contact sports. Bacterial diseases caused by wastewater discharges include, typhoid, paratyphoid, cholera, and bacillary dysentery. The main waterborne viral diseases are viral gastroenteritis and infectious hepatitis. Common protozoans cause amoebic dysentery and giardiasis (WPCF, 1984:1).

The disinfection process is the last step in wastewater treatment (See Figure 1). Disinfection of wastewater is very important to public health because diseases can be transmitted to man directly and indirectly through contaminated drinking water or water for irrigation, recreation, or food processing. The California Department of Health considers disinfection to be the most important stage of wastewater treatment as it is the last barrier to protect receiving water from pathogenic organisms (WPCF, 1984:1).

Disinfection is the selective destruction of disease-causing organisms, it is not the destruction of all organisms, as in sterilization. Disinfection may be carried out by the use of chemical agents, physical agents, mechanical means, and radiation. The most common method of accomplishing disinfection is by the addition of chlorine.

Chemical agents must be safe to handle and apply, and the concentration in the treated water must be measurable. Some common chemical agents include: chlorine and its compounds, bromine, iodine, ozone, phenols and phenolic compounds, and alcohols. Of these, the oxidizing chemicals are the most common and chlorine is the most popular (WPCF, 1984:3).

Physical agents used are heat and light. For example, we heat water to boiling to destroy the major disease producing non-spore bacteria. However, heat is not a feasible means of disinfection for wastewater because of the large quantities of water and the high cost of generating the heat necessary. Ultraviolet radiation can be used and is gaining popularity, particularly in California.

Mechanical means used in the treatment of wastewater that can also aid the disinfection process include: screens,

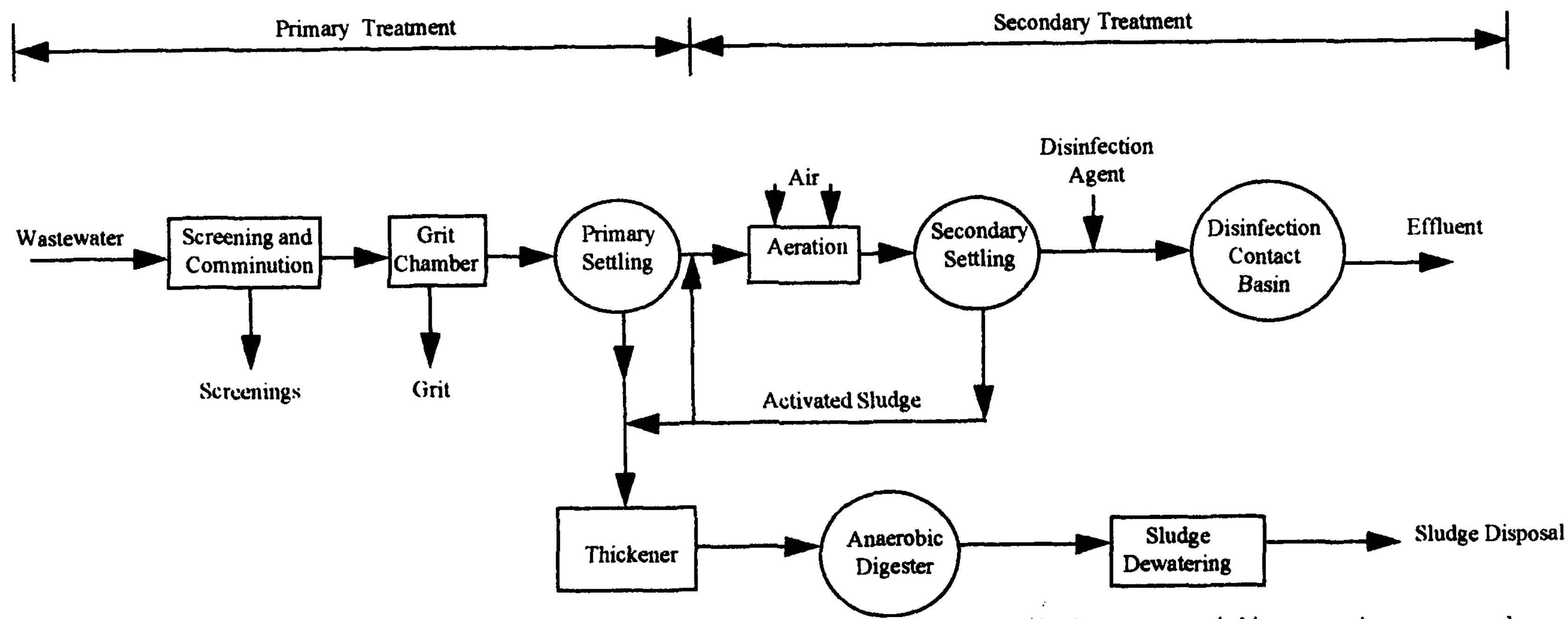

Figure 1. Schematic of an example wastewater treatment facility providing primary and secondary treatment using the activated sludge process. (Masters, 1991:242)

grit chambers, trickling filters, plain sedimentation, chemical precipitation, and activated sludge.

The major types of radiation that can be used include electromagnetic, acoustic, and particle. Because of the penetration power, gamma rays have been successfully used to disinfect both drinking water and wastewater.

Mechanisms of Disinfectants

Four mechanisms have been proposed to explain the action of disinfectants, they include: damage to cell wall, alteration of cell permeability, alteration of the colloidal nature of the protoplasm, and inhibition of enzyme activity (Metcalf, 1979:287). Damage to the cell wall results in cell lysis and death. Altering the cytoplasmic membrane destroys its selective permeability and allows vital nutrients, such as nitrogen and phosphorus, to escape. Heat coagulates the cell protein and acids or bases will denature proteins, producing a lethal effect. Oxidizing agents, such as chlorine, can alter the chemical arrangement of enzymes and inactivate the enzymes. Ultraviolet radiation relies on the transferance of electromagnetic energy from a source to an organism's genetic material. The lethal effects of this energy result primarily from the cell's inability to replicate (EPA, 1986:158).

Factors Influencing the Action of Disinfectants

The following factors must be considered when applying disinfection agents: contact time, concentration and type of chemical agent, intensity and nature of physical agent, temperature, number of organisms, and the nature of suspending liquid (Metcalf, 1979:288). The most important of the above factors is contact time, since disinfection is a time-dependent process. It is generally accepted that the longer the contact time the greater the kill of organisms. Contact time is determined as follows:

$$\text{Contact time (min)} = \frac{\text{Volume of Contact Chamber (gal)}}{\text{Flow Rate (gpm)}}$$

A great deal of information that is required for the design of a disinfection system. Some of this required knowledge includes the rate of inactivation of the target organism(s) by the disinfectant. The effect of the disinfectant concentration on the rate of the process determines the most efficient combination of contact time and disinfectant dose to use (EPA, 1986:21). H. Chick first recognized the similarity of microbial inactivation by chemical disinfectants to chemical reactions. Chick stated that "disinfection is a gradual process, without any sudden effects, and if the disinfectant is sufficiently dilute to admit a reasonable time being taken for the process, the reaction velocity can be studied by enumerating the surviving organisms at successive intervals of time" (EPA, 1986:21). For a given number or organisms and chemical disinfectants, the rate of disinfection can be described by:

$$-\frac{dN}{dt}=kN$$

where:

$$-\frac{dN}{dt}=\textit{rate of change in organism population}$$

k = organism die-off rate constant
N = number of surviving organisms per unit volume at any given time (EPA, 1986:22)

The above equation expresses the rate of die-off of microorganisms as an empirical first order kinetic model and is referred to as Chick's Law. Figure 2 presents Chick's Law graphically.

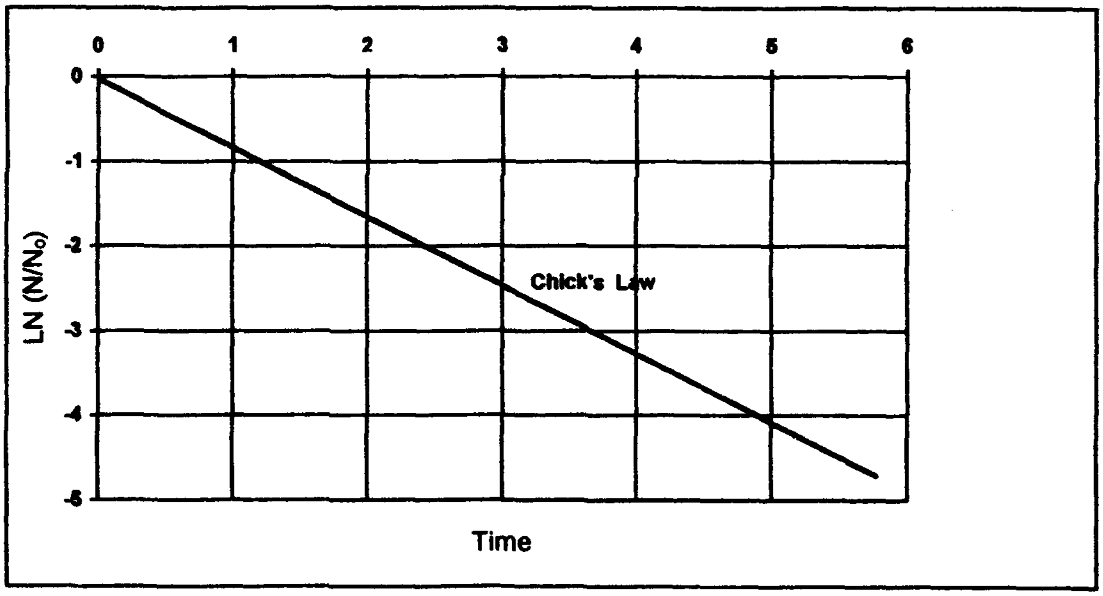

Figure 2. Chick's Law. (Adapted from EPA, 1986:22)

Chick's Law does not apply to all microorganisms, the experiments were conducted with spores and there are no known waterborne diseases that are caused by spores. "Chick's Law does not accurately predict coliform numbers as a function of dose in real world, continuous flow systems, and therefore, the kinetics of disinfection, as with any process, must be determined experimentally" (EPA, 1986:23).

Chlorination

The choice of disinfectant materials depends on their effectiveness for the particular effluent to be disinfected, cost practicality, and potential adverse side effects. For many years plant designers have selected chlorine because of its ability to disinfect wastewater with relatively low dosages (2 to 8 mg/L for activated sludge effluents), its simple feed and control procedures, and its low cost, compared to other substances (WPCF, 1990:822). For these reasons, chlorine is the most commonly used disinfectant throughout the world.

Chlorine is a greenish-yellow gas that can combine directly with nearly all elements. The most common chlorine compounds used in wastewater treatment plants are chlorine gas (Cl_2), calcium hypochlorite [$Ca(OCl)_2$], sodium hypochlorite (NaOCl), and chlorine dioxide (ClO_2) (Metcalf, 1979:292). When chlorine in the form of Cl_2 gas is added to water, hydrolysis and ionization take place, as follows:

Hydrolysis: $Cl_2 + H_2O \Leftrightarrow HOCl + H^+ + Cl^-$

Ionization: $HOCl \Leftrightarrow H^+ + OCl^-$

The quantity of HOCl and OCl^- that is present in water is called the free available chlorine. The distribution of these two species is very important because the killing (disinfection) efficiency of HOCl is approximately 40 to 80 times that of OCl^- (Metcalf, 1979:293). The distribution of

$HOCl$ and OCl^- varies with the pH value of the wastewater. As pH increases the percentage of OCl^- increases and the percentage of $HOCl$ decreases, and vice versa. This distribution is equal at approximately a pH of 8.0.

Untreated wastewater contains nitrogen in the form of ammonia and various combined organic forms. Wastewater effluent also contains significant amounts of nitrogen, usually in the form of ammonia, or nitrate. Hypochlorus acid ($HOCl$) is a very active oxidizing agent and reacts readily with ammonia in the wastewater to form chloramines. The chlorine in these compounds is called combined available chlorine which also serves to disinfect, although at slower rates.

Current practices require that enough chlorine is added to obtain a free chlorine residual assuring that disinfection is carried out. Some factors that affect the disinfection efficiency of chlorine include: the germicidal efficiency of chlorine, the germicidal efficiency of the various chlorine compounds, the importance of initial mixing, the breakpoint reaction, the contact time, the characteristics of the wastewater, and the characteristics of the microorganisms (Metcalf, 1979:297). The breakpoint denotes the amount of chlorine that must be added to a wastewater before a stable free residual can be obtained, however, it is the chlorine residual that has been found to cause the formation of chloramines and trihalomethanes, that do not disinfect and are more toxic than chlorine. The characteristics of wastewater that affect chlorination include BOD, COD, total suspended solids (TSS), organics, and nitrogen. The effectiveness of chlorination varies greatly with the type treatment plant, the quality of the influent, and the required effluent quality.

Of the various chemicals and substances present in a domestic WWTP, chlorine is perhaps the most dangerous. Chlorine is a highly toxic gas which, if inhaled, can injure or kill quickly. Chlorine gas will react with moisture in the air to form hydrochloric acid which can irritate the skin. Chlorine is a regulated hazardous material with a reportable quantity of 10 pounds (49 CFR, 1993:235). Chlorine is immediately dangerous to life and health at a concentration of 10 parts per million (ppm) and has a threshold limit value of 0.5 ppm (3M, 1992:11). A major chlorine leak at a WWTP, if not handled properly, can injure or kill plant personnel and may require evacuation of facility neighbors. WWTP employees must be trained in the proper handling and safety aspects of chlorine and inform neighbors and local government agencies of the physical system, chlorine safety awareness, and emergency procedures.

Dechlorination

Dechlorination is the practice of removing the total free and combined chlorine residual that exists after chlorination. For many plants, dechlorination of final effluent is required to meet chlorine residual permit requirements. Sulfur dioxide (SO_2), sodium metabisulfite, and sodium bisulfite are used for dechlorinating chlorinated effluents, but sulfur dioxide is the favored candidate for dechlorination where polishing is used for the removal of ammonia nitrogen. Sulfur dioxide is a deadly gas which attacks the central nervous system, it is nonflammable, colorless, is immediately dangerous to life and health at 100 ppm, and has a threshold limit value of 2 ppm (3M, 1992:34). Sodium metabisulfite and sodium bisulfite are safe substitutes for sulfur dioxide and are used in most small facilities. These solid dechlorination materials are dissolved and then fed with a chemical feed pump and can be more difficult to control than the sulfur dioxide system.

Hydrogen peroxide (H_2O_2) is an alternative to sulfur dioxide and has the advantage of creating harmless byproducts (oxygen and water), but it is dangerous to handle in its concentrated form (WPCF, 1990:847). Sulfur dioxide gas successively removes free chlorine, monochloramine, dichloramine, and nitrogen trichloride (Metcalf, 1979:304). Approximately 1.0 ppm of sulfur dioxide is required for the dechlorination of 1.0 ppm of chlorine residue. Contact time is generally not a factor since the reaction takes place almost instantaneously. It is important to avoid excess sulfur dioxide dosages to avoid wasting chemicals and because of the oxygen demand exerted by the excess sulfur dioxide, which results in an increase in the measured BOD and COD, and potentially a drop in pH (Metcalf, 1979:305). Sulfur dioxide dechlorination systems are similar to chlorination systems because sulfur dioxide equipment is interchangeable with chlorination equipment. The key control parameters include proper dosage based on precise monitoring of the combined chlorine residual and adequate mixing at the point of application of sulfur dioxide.

<u>Ozone</u>

Ozone (O_3) has been used for disinfection of water since the early 1900's and has found increased use for disinfection of wastewaters. Ozone forms naturally in the atmosphere from photochemical and electrical processes (WPCF, 1990:862). Ozone is produced when a high voltage is imposed across a discharge gap in the presence of a gas containing oxygen (Metcalf, 1979:306). Ozone is a toxic, unstable gas with a short half-life, and must be generated at the point of use. A powerful oxidant, ozone has proven effective in color removal due to its bleaching action and the breakdown and removal of iron and manganese compounds, as well as and odor and taste control. It is suggested that ozone inactivates bacteria by totally or partially destroying the cell wall; this is followed by lysis of the cell (WPCF, 1984:30). The reactive properties of ozone are due to the trivalent form of oxygen. This form is both unstable as a gas and in solution with water (WPCF, 1984:29). When ozone is added to water, it rapidly reverts to oxygen as follows:

$$2O_3 \rightarrow 2O_2 + 2O^* \rightarrow 3O_2$$

Because of this reaction, no concentration of ozone persists in the treated effluent that may require removal or demonstrate that ozone was actually used to disinfect, as is the case with chlorine residuals (Metcalf, 1979:306).

The solubility of ozone in a liquid is governed by Henry's law, which states:

> "the weight of any gas that will dissolve in a given volume of a liquid, at constant temperature, is directly proportional to the partial pressure that the gas exerts above the liquid".

$$H = \frac{mg\ gas / L\ gas}{mg\ gas / L\ liquid} \qquad \text{(Venosa, 1983:461)}$$

Simply stated, Henry's law expresses the concentration of gas above the liquid that must exist in order for a given concentration of gas to be dissolved in the liquid. The lower the value of H, the more soluble the gas is. At 20°C, oxygen has an H value of 29.9 in water, while ozone has an H value of 2.59. In other words, only 2.6 mg/L ozone in air is required to maintain 1.0 mg/L ozone in water, while approximately 30 mg/L oxygen in air is required to maintain 1.0 mg/L in water under equilibrium conditions at 20°C and 1 atmosphere pressure. From a realistic standpoint, the efficiency of production of ozone in air above approximately

1.0% by weight % (12.1 mg/L at 20°C) decreases substantially. As a result, only 4.7 mg/L is the maximum concentration that can be expected to dissolve in the water at that concentration in air, assuming 100% mass transfer efficiency and a demand free water. Even though ozone is more soluble than oxygen, with air as the carrier gas, less will dissolve on an absolute basis because of the lower concentration in air. This exemplifies the need to achieve the maximum possible contactor efficiency, because of the difficulty of maintaining high partial pressures of ozone above the process liquid (Venosa, 1983:461).

Transfer efficiency (TE) is an inherent property of a contactor and is a function of the gas flow rate relative to the liquid flow rate. TE is defined as follows:

$$TE = \frac{100 * (Y_1 - Y_2)}{Y_1}$$

where:
Y_1 = mg O_3 /L inlet carrier gas
Y_2 = mg O_3 /L exhaust gas

TE is the fraction of ozone in the gas that has been transferred to the liquid, expressed as a percent. The applied dose is defined as follows:

$$D = \frac{Y_1 Q_G}{Q_L}$$

where:
Q_G = gas flow rate, L/min
Q_L = liquid flow rate, L/min

The applied dose multiplied by the fraction transferred is the absorbed dose or the transfer:

$$T = Y_1 Q_G / Q_L (Y_1 - Y_2) / Y_1$$
$$T = Q_G / Q_L (Y_1 - Y_2)$$

where:
T = the amount of ozone transferred to the liquid, mg/L.

The applied dose equation demonstrates that the applied dose can be varied either by changing the Y_1 or the Q_G / Q_L ratio. TE, as a function of applied dose, varies greatly, depending on the type of contactor and method of varying the dose. TE decreases much more rapidly when the Q_G / Q_L ratio is increased than when the Y_1 is increased. Thus, an increase in the gas flow rate may not result in a corresponding increase in the absorbed dose.

Applying Henry's law and the concept of TE is very useful for designing and optimizing ozone contactors. Venosa has shown on theoretical grounds, that better TE is possible in a plug flow contactor operating with gas flow counter-current to liquid, and in a field study it was found that the best gas liquid contactor with respect to mass transfer efficiency was a multiple injection bubble diffuser with counter-current flow configuration (Venosa, 1983:462).

The capability of the ozone contacting unit is critical to the successful performance of the ozone disinfection system. The bubble diffuser ozone contactor is the most commonly utilized reactor for disinfection with ozone. See schematic of ozone bubble diffuser shown in Figure 3. There are several important design considerations that must be considered to maximize ozone transfer and disinfection performance, these considerations are as follows:

a) the contact basin should be as deep as possible
b) bubbles should range between 2 and 3 mm in diameter
c) contactor should have at least two independent trains, or compartments
d) contactor should simulate plug flow and minimize short-circuiting
e) contactor should have from 4 to 6 ft of head space
f) each set of diffusers should have a flow control valve and separate flow measurement
g) wastewater flow should be counter-current to the ozonized air flow
h) contact basins should be made of concrete
i) contact basins should be covered and sealed as much as possible
j) stainless steel piping for ozonized gas flow must be provided
k) ozonized feed-gas and contact basin off-gas sample lines should be stainless steel tubing. (EPA, 1986:136)

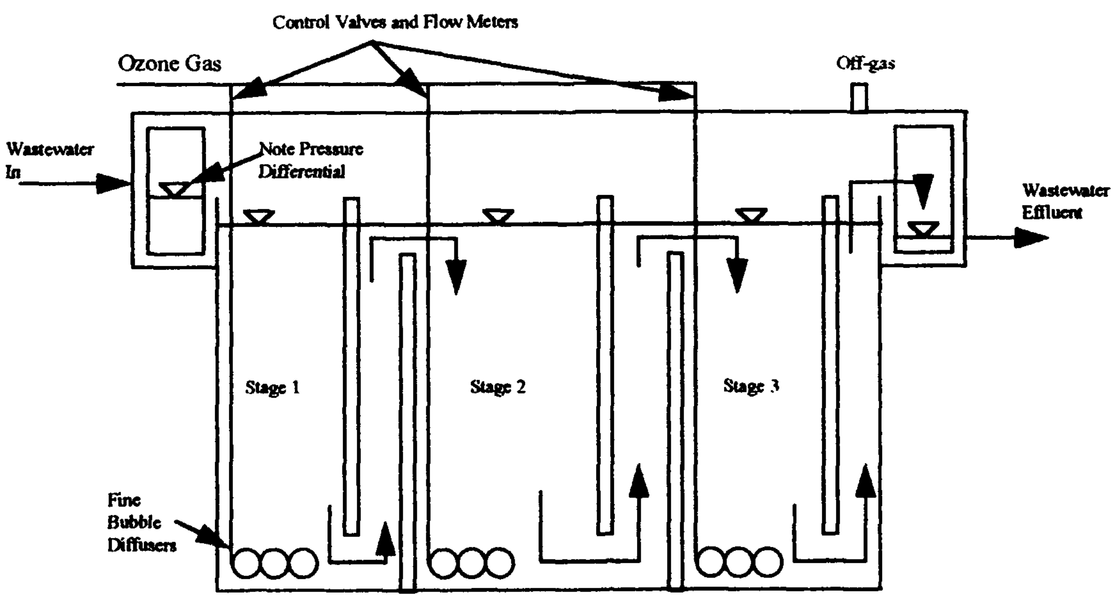

Figure 3. Schematic of a 3-stage, bubble diffuser ozone contact basin (EPA, 1986:135).

Some of the advantages of using ozone rather than chlorine include:

a) a high germicidal effectiveness, even against resistant organisms such as viruses and cysts.

b) on decomposition, the only residual material is more dissolved oxygen.

c) no dissolved solids, such as chlorides, are added.

d) its disinfecting power is not affected by pH or ammonia content.

e) no need to store or transport toxic chemicals at the site.

Some disadvantages of ozone disinfection include:

a) ozonation system requires a higher capital and operational cost than chlorine

b) pilot plant testing is required to determine required ozone dosage

c) competitive oxidant demands of certain industrial wastes may render ozone disinfection uneconomical. (WPCF, 1984:30)

There are three basic ways to generate and use ozone in wastewater treatment: generation from air, generation from supplied oxygen and recycled oxygen to the ozone generation system, and generation from oxygen used for oxygen activated sludge system and recycle oxygen to the activated sludge system (Rakness, 1984:1152). Ozone must be produced continuously and used as it is produced because it is unstable and cannot be stored.

Ultraviolet Light Disinfection

Sunlight has always acted as a natural disinfectant, it is the ultraviolet rays that destroy a wide range of microorganisms. Microbiologists, chemists and engineers have been developing and refining the technology needed to harness ultraviolet energy to kill bacteria and viruses in water and wastewater (Trojan, undated:1). Used properly, ultraviolet light can effectively destroy bacteria, viruses, algae and other microorganisms in water and wastewater, without the use of chemicals. The germicidal effects of ultraviolet light involve photochemical damage to ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) within the cells of an organism (Darby, 1993:169). Ultraviolet light as a disinfectant has been used as an alternative to chlorine in many eastern and midwestern states (Darby, 1993:169).

Ultraviolet lamps produce nearly monochromatic light at a wavelength of 253.7 nanometers (nm), which is in the optimal range for producing germicidal effects. The nucleic acids in microorganisms are the most important absorbers of the energy of light in the wavelength range of 240-280 nm (Darby, 1993:169). Because DNA and RNA carry genetic information for reproduction, damage of these substances can effectively prevent cells from replicating.

The principal parameters that affect ultraviolet performance are the dose (intensity and exposure time) and the characteristics of the wastewater to be disinfected (Darby, 1993:170).

The average intensity within a photoreactor must be determined to obtain an accurate measurement of ultraviolet dose. Some factors that affect ultraviolet intensity include the characteristics of the ultraviolet lamps, the geometry of the reactor, and the fouling characteristics of the wastewater to be disinfected.

As with the other forms of disinfection, the wastewater must have sufficient contact time with the disinfectant. The key is to achieve plug flow so that each flow element resides in the reactor for the same amount of time, of course perfect plug flow will never be achieved, thus, the distribution of exposure times about the ideal time must be minimized (EPA, 1986:159). Short circuiting must be minimized and turbulence is needed to produce adequate mixing and reduce the effect of particle shading on the light emitted by the ultraviolet lamps.

Many of the constituents found in typical wastewater can absorb ultraviolet light and decrease the average intensity within the reactor. Many chemical substances, including phenolic compounds, humic acids, lignin sulfonates, iron, and coloring agents have been reported to interfere with ultraviolet transmission (Darby, 1993:171). It has been found that suspended solids in the range of 5-50 mg/l and turbidity from 0.5-12 NTU had little effect on ultraviolet absorbance (Fahey, 1990:17). "Suspended solids in effluents can harbor or shield organisms, thus lessening the average UV intensity reaching targeted organisms", as illustrated in Figure 4 (Darby, 1993:171).

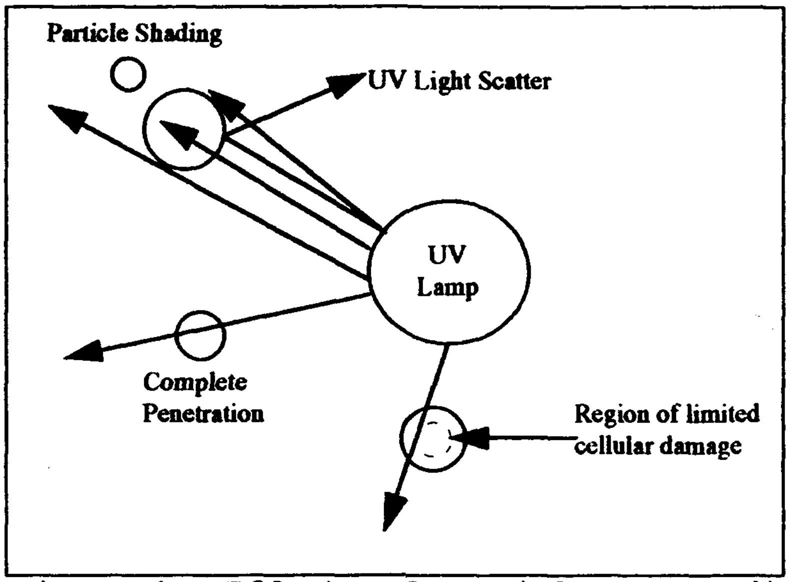

Figure 4. Effects of particles on UV disinfection (Darby, 1993:171).

The UV demand of wastewater is also a critical characteristic. Certain organic and inorganic compounds in wastewater absorb energy at the 253.7 nm wavelength (EPA, 1986:207). The level of absorbance can affect the sizing of a UV system and possibly the spacing of the lamps. The absorbance of wastewater is measured by placing a sample in a quartz cell (transparent to the 253.7 nm wavelength) of a given width. A spectrophotometric measurement of the absorbance is made of a direct beam of light at the required wavelength, which is passed through the quartz cell containing the sample. A detector determines the amount of light which passes through, and by inference, the amount of light absorbed by the sample is determined. The output of this measurement is absorbance units per centimeter (a.u./cm) (EPA, 1986:208).

The transmittance of the wastewater is commonly used to describe the demand of the wastewater. This can be determined from the absorbance measurement, and is often expressed on a percent basis:

$$\% \text{ Transmittance} = 100 * 10^{-(a.u./cm)}$$

Despite the fact that wastewater characteristics are different from site to site, the EPA Design Manual for Municipal Wastewater Disinfection provides ranges of the UV demand for different levels of treatment as shown in Table 1.

Table 1. UV Demand for Different Levels of Wastewater Treatment

	UV Absorbance Coefficient α (cm^{-1})	Percent Transmittance	Absorbance (a.u./cm)
Primary Treatment	0.4 to 0.8	67 to 45	0.174 to 0.35
Secondary Treatment	0.3 to 0.5	74 to 60	0.13 to 0.22
Tertiary Treatment	0.2 to 0.4	82 to 67	0.087 to 0.174

(Adapted From EPA, 1986:159)

Ultraviolet disinfection has several benefits. No chemicals are required to carry out UV disinfection, which results in greater safety for operators of wastewater treatment plants. UV has a greater effectiveness on a wide range of pathogens, a faster treatment time, low operating costs, reduced capital costs, and a simple operating system (a lighting system with no moving parts) (Trojan, undated:4).

Published safety standards and guidance specific to UV disinfection systems at wastewater treatment plants are not available. Despite this fact, there are special concerns and precautions that should be considered in the design of UV disinfection systems, including measures to reduce risk of exposure to UV radiation according to National Institute of Occupational Safety and Health (NIOSH) recommendations. Overexposure to UV radiation can affect unprotected skin. The short term effect from moderate exposure to the skin is called erythema, a condition that reddens the skin (Mann, 1992:45). Excessive exposure may cause blistering or bleeding. The eyes are the most susceptible part of the body, and exposure can result in a condition much like that of seeing the flash from an arc welder, which causes a painful inflammation of the eye. Low pressure UV lamps are particularly dangerous because the low wattage and small visible output make it seem deceptively harmless.

UV disinfection lamps draw a substantial electrical power. Design of UV disinfection systems should consider the power requirements and associated hazards, including the shock hazard and proximity of wastewater to the equipment.

<u>Summary</u>

Each of the disinfection systems described has advantages and disadvantages and feasibility of each depends highly upon the WWTP design, operations, and regulatory agency. Disinfection will always be required to some extent. If the use of chlorine is restricted or banned altogether, an alternative method of disinfection will have to be implemented. Ozone was favored in the 1980's, however, with emerging technologies UV disinfection is becoming more feasible and favored. The decision of selecting an alternative is complex and detailed pilot studies must be carried out. This research is intended to serve as an information guide and basic decision document for determining which alternative should be studied in greater detail.

III. Methodology for Selection of a Disinfection Method

Overview

This chapter outlines the methodology for selecting a method of disinfection. Models for Ultraviolet and Ozone disinfection are presented with respect to pre-selected variables and related to the total coliforms expected in the effluent after disinfection. A method for determining the estimated amount of sulfur dioxide required to carry out dechlorination along with some design considerations is also presented. The reader is reminded that these representations are to be used only as preliminary screening tools and that before a final decision is made on a disinfection method, pilot studies must be accomplished. The range of values for the various parameters are taken from EPA studies, literature, and pilot plant studies.

Data Acquisition

The Air Force owns and operates Wastewater Treatment Plants at several installations throughout the United States. As part of his thesis requirement, Capt Vincent Renaud, AFIT/GEM 87S, conducted an inventory of Air Force WWTPs in 1987. An up to date inventory, was obtained from HQ AFCESA/ENC (Anderson,1994). Mr. Anderson provided a current list of Air Force operated WWTPs. The two lists were cross referenced to obtain an accurate listing of WWTPs. A survey was sent to each of the active duty installations that operate a WWTP. Appendix A contains the survey questions, distribution list, and results obtained from the survey. Of the thirty-four questionnaires sent, only eighteen were returned. Of those eighteen, only one installation no longer operated its WWTP, twelve are using chlorination for the disinfection process, and five do not perform disinfection. See Appendix A for complete results of the survey.

Site Visits

It was desired to visit WWTP's that utilized ozone and ultraviolet disinfection systems to obtain a first hand look at a system in operation. Through telephone conversations it was discovered that the Fairborn, Ohio WWTP was utilizing Ultraviolet disinfection and the Belmont Wastewater Treatment Facility in Indianapolis, Indiana was utilizing an Ozone disinfection system.

Ms. Kathleen M. Cook, supervisor of the plant was contacted (Cook,1994). Ms Cook authorized a site visit. The Fairborn plant is a secondary treatment plant that uses the activated sludge process. The plant is designed to treat a 5.5 MGD with a peak of 16 MGD. The effluent from the plant is discharged directly to the Mad River. The plant disinfects the effluent only during the summer months in order to comply with Ohio EPA requirements (Cook,1994).

The ultraviolet system used at the Fairborn plant is an Infilco Degremont Inc. system. The UV lamps are placed vertically in the disinfection channel, the system consists of 14 modules with each module containing 40 lamps. The modules are split into two channels so that if one channel requires maintenance the other can be used without disruption of the process. One module is capable of disinfecting one million gallons of effluent. The modules are controlled by the flow through the system such that only the required number of modules are operating in order to assure proper disinfection.

The entire system is automatically controlled at the disinfection channels. The system monitors the flow rate from the plant effluent flow meter and maintains the required number of lamps illuminated to achieve desired disinfection. Plant personnel need only view the main control screen for alarm conditions. An automatic level control gate is installed at the beginning of the disinfection channels to assure the proper level of effluent in the channels at all flow conditions.

Maintenance of the system consists of the following:

Daily:
- Check control panel for operating conditions
- Run in-channel air scrub system (twice for 30 minutes)
- Check level of effluent

Monthly:
- Clean UV modules (if necessary)
- Clean module fan grills and shrouds
- Test circuit breakers
- Run all modules in channel for 30 minutes
- Check operating lamp hours

(Infilco, 1993:14-17)

The personnel at the plant stated that it is only necessary to clean the UV modules approximately every six months. The cleaning procedure entails removing the modules and dipping them in a citric acid solution then hand wiping the quartz sleeves dry.

Overall the plant personnel are extremely satisfied with the UV system, it has decreased man-hours required for maintenance and they have not noted any substantial increase in power consumption at the plant. Replacement bulbs cost $60.00/lamp and are warranted by Infilco for one year of service life, since the system is only run for six months out of the year, bulbs generally last for two years. The cost for the system was $365,000 not including design consultant fees. The plant has not experienced a violation of coliform standards since operation of the system began (Cook,1994).

Belmont plant representatives were contacted after attempting to obtain a tour at two other WWTPs that had been utilizing an ozone disinfection system. The first WWTP contacted was the Delaware County plant in Ohio, this plant had ceased using ozone approximately five years ago due to the high costs associated with the system. The second plant was the Southport WWTP in Indianapolis, Indiana; this plant had recently ceased ozone disinfection. They were currently using a chlorination system and were investigating alternative disinfection methods.

Mr. Kevin M. Corsaro, O&M Specialist, provided a tour of the ozone generation facilities and cryogenic plant (Corsaro, 1994). The plant is currently exploring alternative disinfection systems to include UV provided by Infilco, and a pilot ozone system provided by Ozonia of Lodi, New Jersey. The Belmont plant is a tertiary plant with a maximum design flow of 125 MGD and a current average daily flow of approximately 100 MGD. The effluent is discharged to the White River and disinfection is required from 1 April to 31 October. Ozone is generated from high purity oxygen (approximately 99% pure at the time of the site visit) from the cryogenic oxygen facility located at the plant. Disinfection is carried out in two ozone contactors that are approximately 33 feet long, 10 feet wide, with a 16 feet side-water depth, and utilize 2000 bubble diffusers. Weirs have been installed to help promote plug flow through the contactors. The high purity oxygen is fed to two feed-gas compressors, which develop sufficient pressure to force the gas through the rest of the system (Rakness, 1988:216). The high frequency ozone generators are PCI Model B-800, and are cooled with Freon® and water. The use of Freon® is a main concern due to the high costs associated with its use. The contact time in the contactors is approximately seven minutes and the transfer efficiency ranges from 70-80%. The ozonation system power requirements cost approximately $300/day, this does not include power required by the cryogenic plant. Mr. Corsaro stated that the system is self sufficient and requires little maintenance, however, the system is adjusted by operators to avoid excess ozone production. The facility is exploring the possibility of installing new ozone generators that would provide better efficiency, the current piping associated with the current generators does leak occasionally, but does not cause safety concerns. There has only been one safety incident since the system has been in operation and was caused by operator error. The operators are required to have OSHA training, which is provided by plant personnel. Mr. Corsaro was pleased with the current ozone system and believes that the plant will continue to utilize the ozone system with some modifications, mainly the installation of new generators. A UV system for this particular plant would require approximately 10,000 lamps and due to the industrial nature of the influent, fouling would be a major problem. The ozone system provides good odor control. Because of heavy rainfall the turbidity of the effluent was approximately 1.8 NTU at the time of the visit but typically is < 1 NTU.

Choosing an Alternative Disinfection Method/Option

The decision to disinfect or not disinfect is determined on a site-specific basis by regulatory agencies, which makes it impossible to establish universal policies on wastewater disinfection requirements. To determine the need for municipal wastewater disinfection at a particular site involves the investigation of receiving water uses and the associated risks to human health, and assessment of the options that are available for control of fecally-contaminated discharges, and an evaluation of the environmental effects that control measures may create (EPA, 1986:11). Figure 5 presents an approach for the type of rationalization that can be involved in assessing the need for, and consequences of, disinfecting municipal wastewaters (EPA, 1986:12). In general, Figure 5 demonstrates that human health is the primary concern and upon determining the level of risk and the potential for reducing or eliminating the risk, the environmental considerations determine the applicability of the proposed control measures. Choosing an alternative that satisfies both the human health and environmental concerns at a specific site is the next step.

There are many disinfection alternatives that can be considered and have been identified from various publications without regard for physical or operational constraints. The major factors that must be considered when evaluating disinfection alternatives are presented in Table 2.

Of particular concern to the Air Force is the ability to adapt or modify a new disinfection system/method to an older facility; the ease of operation and maintenance; and system flexibility.

Of the 34 Air Force Installations that operate WWTPs, 17 responded to the survey in Appendix A. Of the 17 respondents, 11 utilize chlorination for disinfection and, of these 11, four dechlorinate with sulfur dioxide. With the impending regulations outlined in Chapter 1, the Air Force will need to consider an alternative to chlorination and possibly eliminate chlorination all together.

When considering the disinfection process it is important to consider the entire wastewater treatment system, since "predisinfection processes not only physically remove pathogens from the wastewater, but they also condition the effluent so that it is more amenable to successful disinfection," (Calmer, 1994:40). Thus, it is important to study the entire treatment process before deciding upon a disinfection technology.

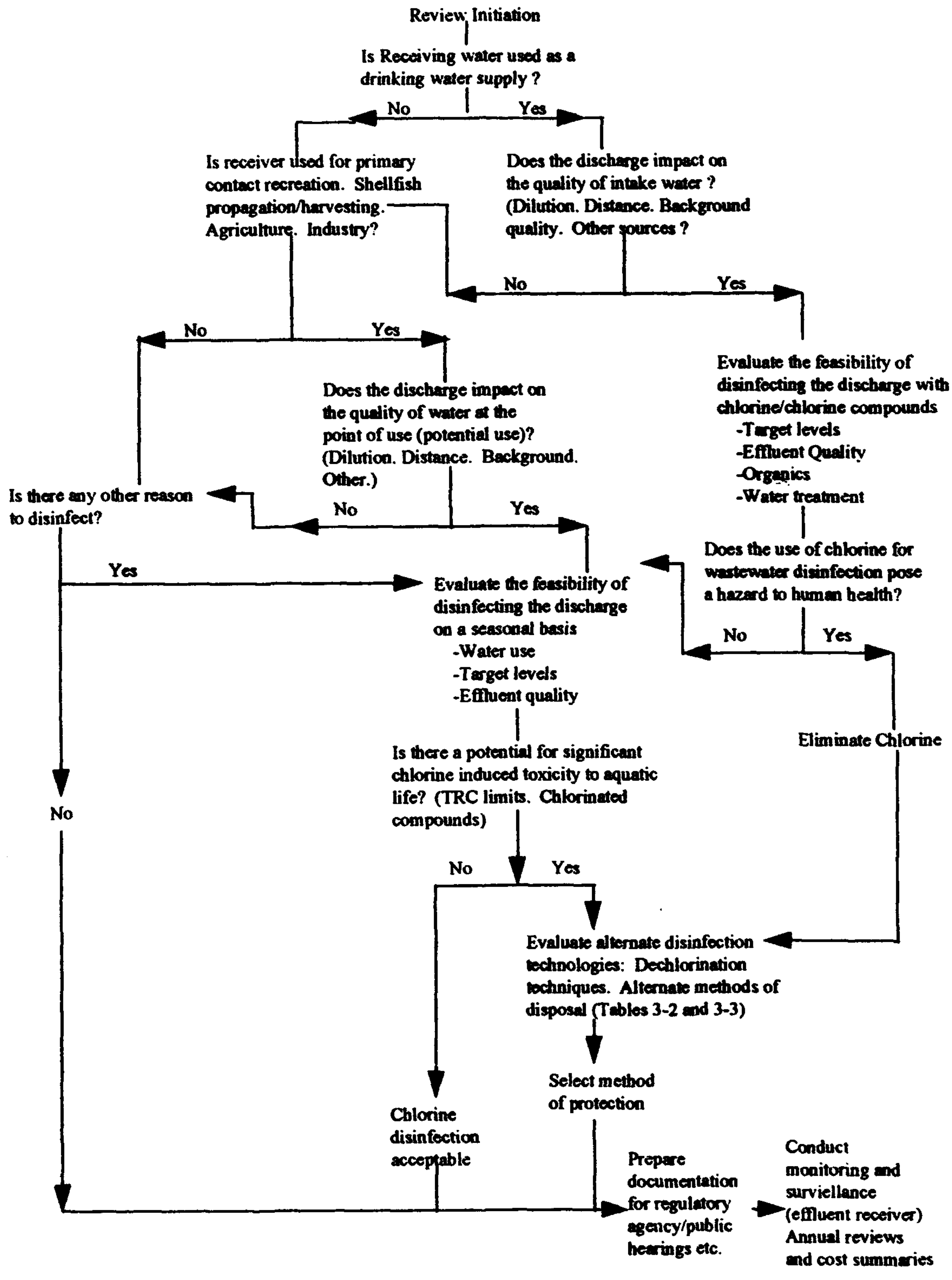

Figure 5. Framework for evaluating site-specific wastewater disinfection requirements. (Adapted From EPA, 1986:12)

Table 2
Major Factors in Evaluating Disinfectant Alternatives

Effectiveness	- Ability to achieve target levels of selected indicator organisms - Broad spectrum disinfecting ability - Reliability
Use-Cost	- Capital cost - Amortization cost - Operating and maintenance cost - Cost of special wastewater pretreatment
Practicality	- Ease of transport and storage, or on-site generation - Ease of application and control - Flexibility - Complexity - Ability to predict results - Safety considerations
Pilot Studies Required	- Dose requirements - Refine design details
Potential Adverse Effects	- Toxicity to aquatic life - Formation and transmission of undesirable bio-accumulating substances - Formation and transmission of toxic, mutagenic, or carcinogenic substances

(EPA, 1986:13)

The first four factors above relate to the disinfection process itself. Potential adverse effects relate to the effects of the disinfectant on the receiving water and other environmental concerns and considerations. Evaluation of the criteria listed in Table 2 above relative to practical, physical, and operational constraints of municipal wastewater disinfection, reduces the available alternatives to chlorination, chlorination/dechlorination with sulfur dioxide, ozone, and ultraviolet light (EPA, 1986:11). The EPA recommends two levels of review in order to properly evaluate and select alternative disinfection systems. The first level of review involves the consideration of several non-monetary factors, which includes three primary components, including technical factors, environmental impacts, and safety. In assessing the disinfection alternatives with respect to their non-monetary factors, the EPA uses a qualitative matrix approach, shown in Table 3. When this document was published in 1986, ozone and ultraviolet disinfection were still in development. In the table, the process control category for each was changed from developing to fairly well developed due to the number of WWTPs currently using these technologies. In Table 3 under contact time, long can be defined as approximately thirty minutes while short can be a few seconds. A relative ranking of the alternatives based on this qualitative assessment can also be made, as shown in Table 4. The ranking scale is based on a scale of one to five, with one indicating the least impact or best degree of confidence. From these types of analyses, the number of appropriate alternatives can be narrowed, and some alternatives may be completely eliminated.

Table 3
Applicability of Alternative Disinfection Techniques

Consideration	**Cl_2**	**Cl_2/de Cl_2**	**O_3**	**UV**
Size of plant	all sizes	all sizes	medium to large	small to medium
Applicable level of treatment prior to disinfection	all levels	all levels	secondary	secondary
Equipment Reliability	good	fair to good	fair to good	fair to good
Process Control	well developed	fairly well developed	fairly well developed	fairly well developed
Relative Complexity of Technology	simple to moderate	moderate	complex	simple to moderate
Safety Concerns	yes	yes	no	no
Transportation on site	substantial	substantial	no	minimal
Bactericidal	good	good	good	good
Virucidal	poor	poor	good	good
Fish Toxicity	toxic	non-toxic	none expected	non-toxic
Hazardous By-products	yes	yes	none expected	no
Persistent Residual	long	none	none	none
Contact Time	long	long	moderate	short
Contributes Dissolved Oxygen	no	no	yes	no
Reacts with Ammonia	yes	yes	yes (high pH only)	no
Color removal	moderate	moderate	yes	no
Increased Dissolved Solids	yes	yes	no	no
pH Dependent	yes	yes	slight (high pH)	no
Operation & Maintenance Sensitive	minimal	moderate	high	moderate
Corrosive	yes	yes	yes	no

(Adapted From EPA, 1986:14)

Table 4
Technical Factors and Feasibility Considerations

Considerations	Cl_2	Cl/de Cl_2	O_3	UV
Flexibility	2	2	2	2
Reliability	1	2	3	2
Complexity	2	2	3	2
Effectiveness	2	2	1	2
Pilot Studies (Required)	1	1	3	3

* Rating based on scale of 1 to 5, with 1 indicating best degree of confidence (Adapted from EPA, 1986:14).

The alternatives that remain after the first level of review can then be evaluated in the second, more detailed, review. The second level involves development of a preliminary design, cost estimates, and an economic analysis comparing the alternatives on an equitable basis. Detailed capital and operation and maintenance costs can be developed for each alternative disinfection system. Capital costs include structures, process equipment, major auxiliary equipment, special foundation requirements, electrical and instrumentation, site work, miscellaneous process and piping, construction contingencies, engineering, project administration, and interest during the estimated period of construction. The operation and maintenance costs are annualized and include labor, electrical power, chemicals, routine equipment maintenance, and materials and supplies (EPA, 1986:11).

Preliminary Ultraviolet Disinfection Design

There are two basic reactor designs for UV disinfection. The first design encases the lamps in quartz sleeves which are submerged in the wastewater at all times (See Figure 6). In the second design, wastewater flows through Teflon® tubes and the lamps are located outside and parallel to the Teflon® tubes (See Figure 7). The maximum use of the reactor volume is of the greatest importance in UV disinfection systems (Hegg, 1990:126). If the system does not provide the desired level of disinfection, there may be dead zones or short-circuited areas. This problem can be identified by performing dye tracer studies. With a proper design the velocity should be equivalent at all points upon entering and exiting the reactor. The use of weirs and baffles can ensure that these conditions are met.

The dosage of UV light available to kill bacteria is measured in $mW\text{-}s/cm^2$. The killing effectiveness of UV depends upon the intensity of the light and the time in contact with the organism. Figure 8 shows the relationship between lamp output and lamp life. Any condition that reduces either the intensity of the light or the contact time will decrease the performance of the UV disinfection system (WPCF, 1990:851). The flow rate of the wastewater affects the contact time. Increasing the flow rate of the wastewater decreases the contact time and lowers the disinfection efficiency. Therefore, UV systems are designed to disinfect at the peak rate of flow.

The characteristics of the wastewater being disinfected also affect the disinfection performance. The two qualities of the wastewater passing through the disinfection reactor that most affect performance are UV transmission and the amount of suspended solids. UV transmission, defined as the percentage of UV light not absorbed after passing

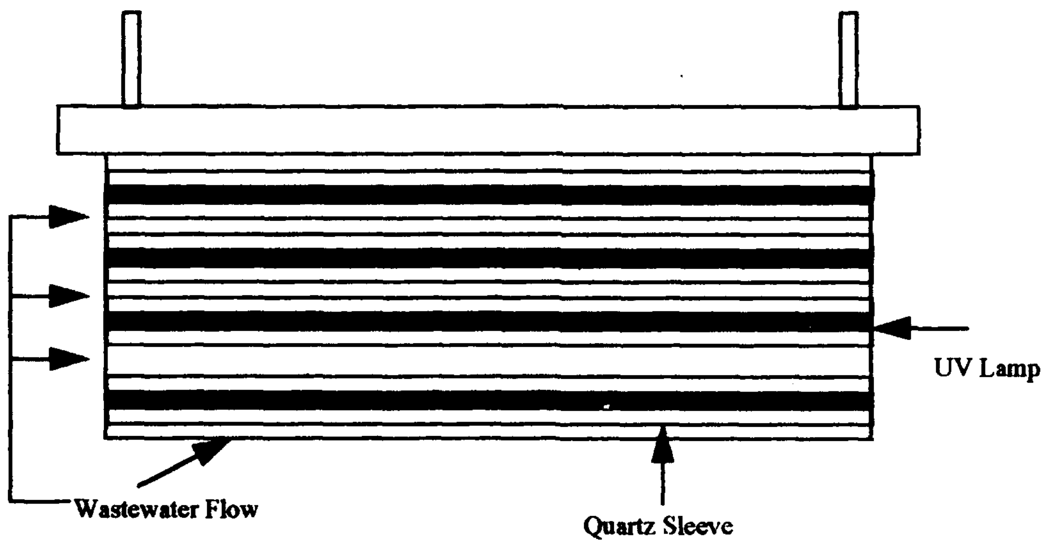

Figure 6. Schematic of an open-channel, modular UV unit with lamps encased in teflon tubes. Wastewater flows around the lamps (Adapted From EPA, 1986:163).

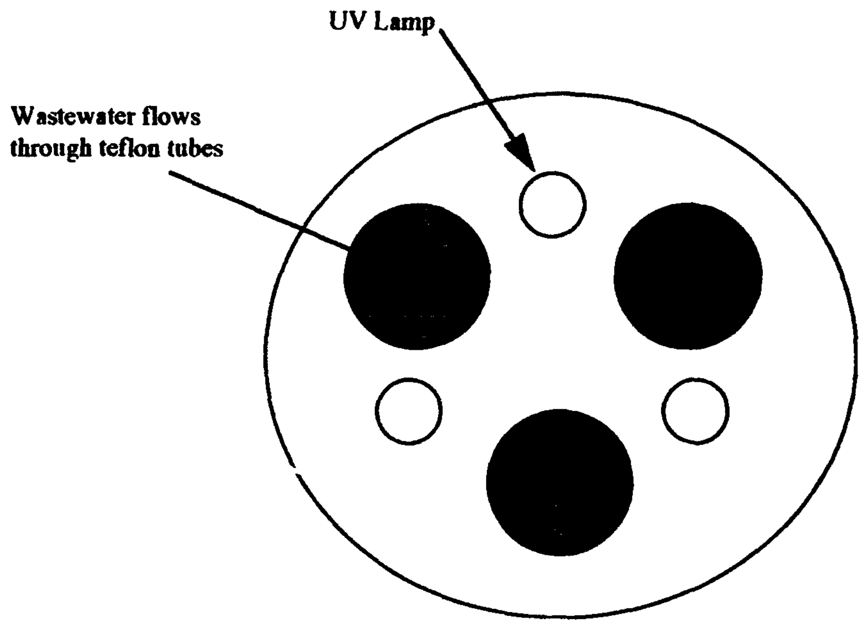

Figure 7. Cross section of UV system with wastewater flowing through teflon tubes surrounded by UV lamps (Qualls, 1989:318).

through 1 cm of water, depends on dissolved and suspended matter and color (WPCF, 1990:851). Mr. Jim Considine of Fisher & Porter Ltd. stated that "a minimum of 60% transmittance is required for effective disinfection with UV" (Considine,1994). If transmittance is reduced, so is the intensity of the light reaching the bacteria, thus resulting in a decreased kill or decreased disinfection efficiency. Transmittance generally improves with increasing degree of treatment, and domestic effluents typically have a higher UV transmittance than industrial effluents. Figure 9 shows the relationship between UV intensity and transmittance of water. Mann found that the number of UV lamps required increases exponentially as wastewater's transmittance decreases, an effluent with a UV transmittance of 50% can require twice as many lamps as an effluent with a transmittance of 65%. Thus, wastewater with an extremely low transmittance can make UV disinfection too expensive or impractical (Mann, 1992:42).

Suspended solids, also referred to as filterable residue, represent the weight of solids remaining on a glass fiber filter following filtration and drying at 103 to 105°C (Franson, 1992:2-56). Suspended solids can lower the UV transmission by scattering and absorbing the light and can also reduce disinfection efficiency by encapsulating the bacteria and protecting them from exposure to the UV light (See Figure 3). Water that appears clear in visible light can also absorb invisible UV wavelengths, thus visual clarity is not always a good indicator of UV transmission (WPCF, 1990:852).

Estimating labor requirements is a very subjective task and for UV systems can be divided into three major categories as follows:

a) Operations and Monitoring
   - daily system checks
   - data recording
   - sampling and analysis for suspended solids, bacterial density, and UV absorbance
   - direct manual control of the system, or the monitoring and control of automatic operational instrumentation

b) General Maintenance
- check and maintain system components
- storage and maintenance of appropriate parts
- routine systems cleaning
- replacement of worn or broken components in the system

c) System Overhaul (once/year)
- clean the outside surface of each lamp
- clean quartz sleeves and teflon tubes
- measure relative output of each lamp
- measure quartz/Teflon® enclosures for transmittance
- check internal components for wear

(EPA, 1986:243)

The labor needs associated with a and b above have been estimated to range from 2-3 hr/wk for small systems (less than 100 lamps) to 15-30 hr/wk for larger plants (greater than 1500 lamps) (EPA, 1986:243). Figure 10 represents the total yearly estimated labor requirement based on previous studies. "Overall, the labor needs for the UV process are relatively low, ranging from approximately 40 mandays/year for a small 10 kW (120 lamps) system to approximately 400 mandays/year for a 400 kW system (5000 lamps)" (EPA, 1986:243).

The dose of UV represents the product of the rate of energy emission (lamp intensity) and the time the organisms are exposed to the germicidal energy at 253.7 nm.

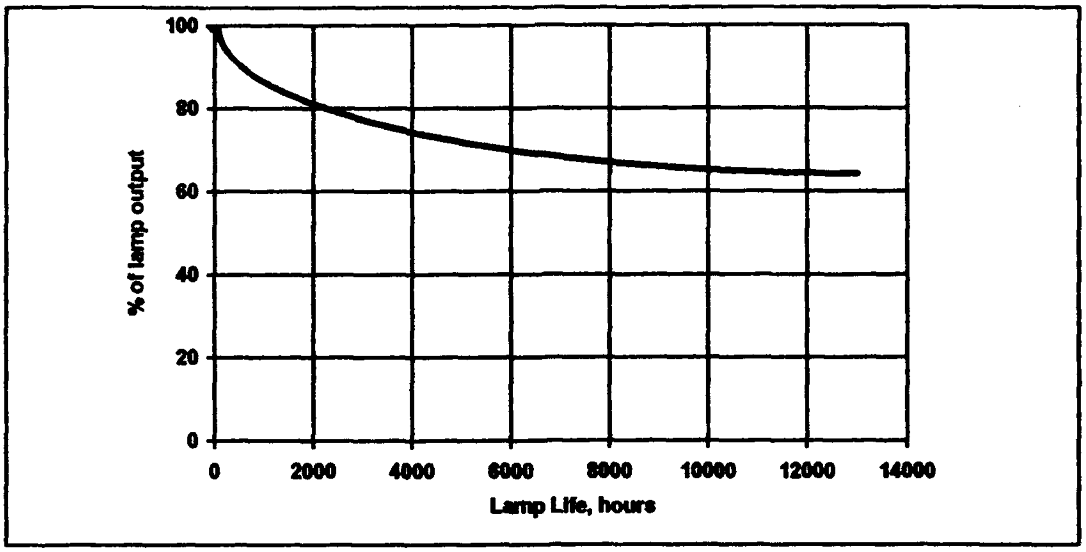

Figure 8. Estimated Decline in Lamp Output with Age
(Adapted From WPCF, 1984:3)

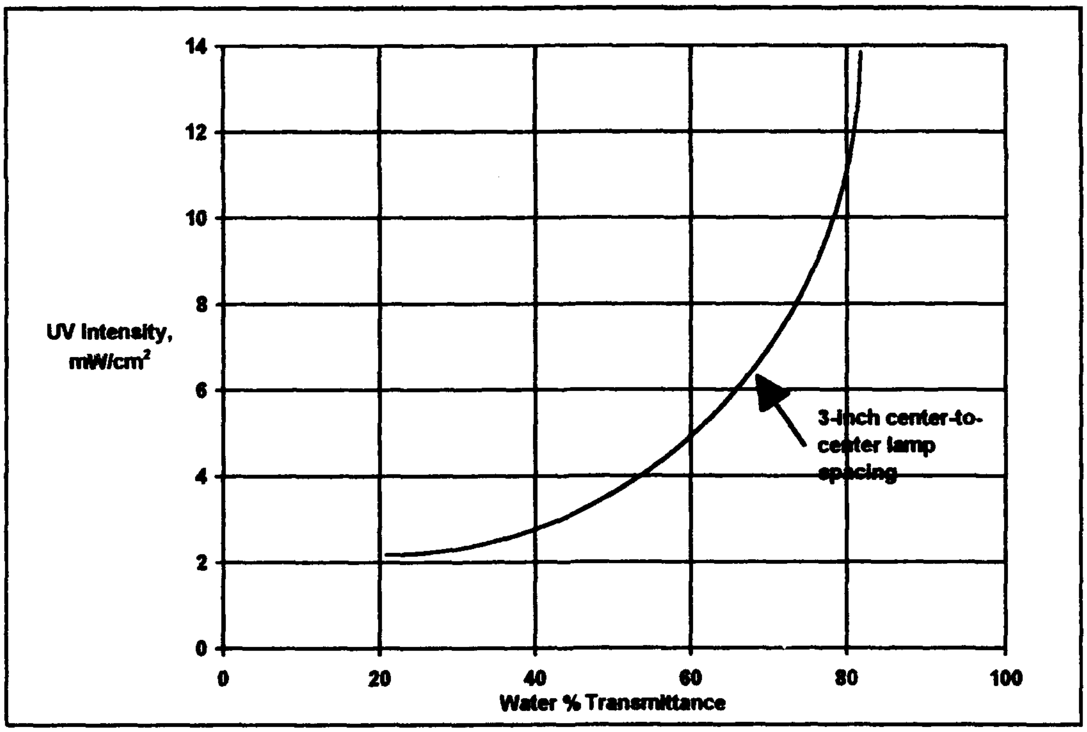

Figure 9. UV Intensity versus Water Percent Transmittance
(Adapted From WPCF, 1984:3)

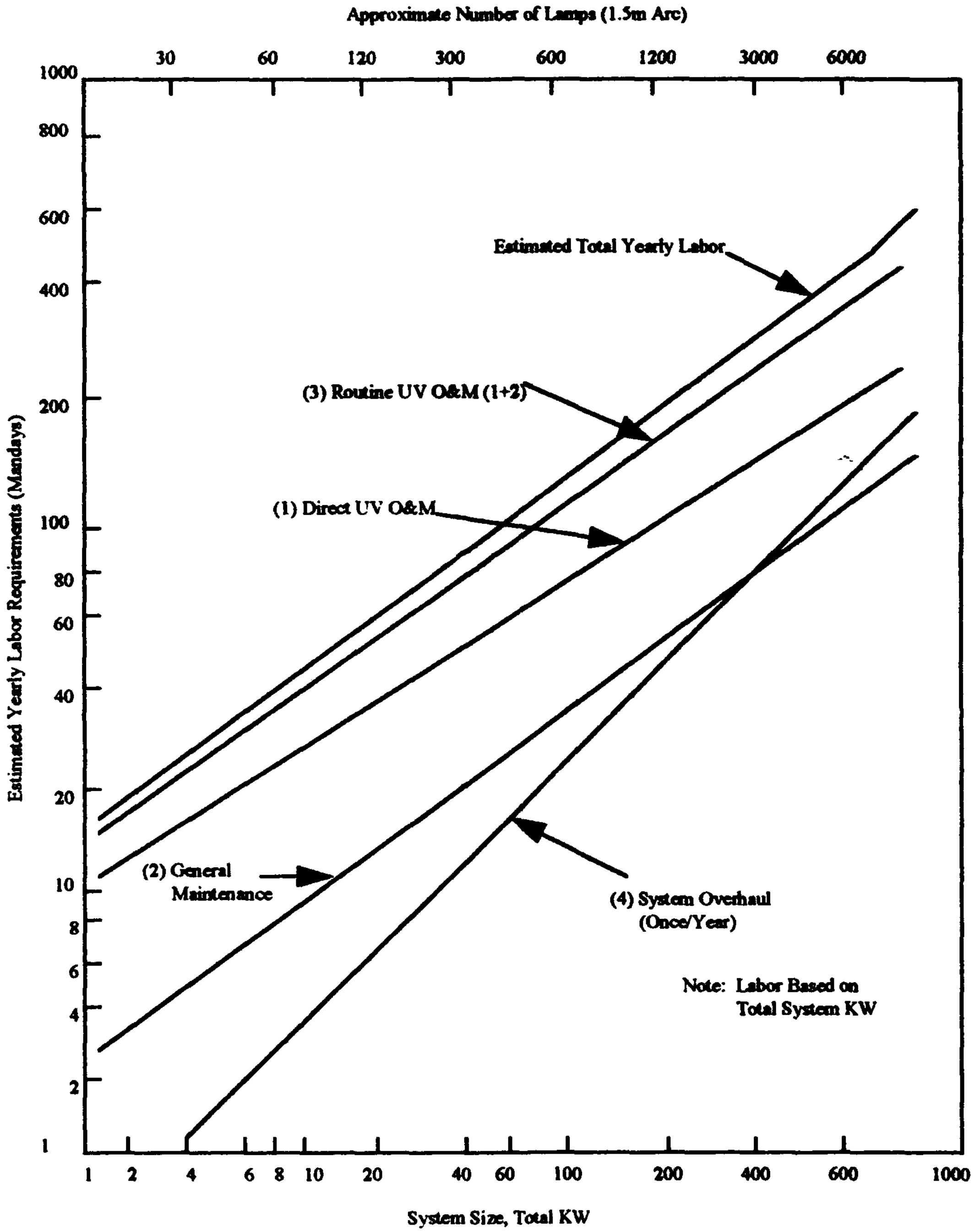

Figure 10. Estimate of labor requirements for the operation and maintenance of UV systems (Adapted From EPA, 1986:244).

The equation for calculating UV dose is as follows:

$$D = It$$

where:

D = dose, mW-s/cm^2

I = lamp irradiation, mW-s/cm^2 at 253.7 nm wavelength; and

t = exposure time, seconds.

(WPCF, 1990:852)

The performance of UV systems for the inactivation of fecal coliform indicator organisms can be analyzed using the EPA Process Design Equation model, which is expressed as follows:

$$N = N_o \exp [ux/2E \{1 - (1 + 4E\, aI_{avg}{}^b/u^2)^{1/2}\}] + cSS^m$$

where:

N, N_o are the final and initial bacterial densities, respectively (colony forming units, *CFU*, per *100 ml*)

u is the superficial forward velocity, computed as volumetric flow divided by wetted cross-sectional area (cm/s).

$$u = \frac{x}{V * Q}$$

where: V is the volume of the reactor and Q is the total flow (liters/second)

x is the characteristic reactor length in the direction of flow under exposure to UV light (cm)

E is the dispersion coefficient, representative of UV reactor hydraulic behavior (cm^2/s)

I_{avg} is the computed average reactor intensity, defined as a function of the UV absorbance (or, conversely, UV transmittance) of the wastewater (μW/cm^2)

SS is the suspended solids concentration of the wastewater (mg/L)

a, b are empirical constants defining the rate of inactivation as a function of average reactor UV intensity

c, m are empirical constants defining residual particulate associated bacterial density as a function of wastewater suspended solids

In effect, this model establishes design on the basis of the system configuration (u, x, E, I_{avg}), and wastewater quality and quantity (N_o, Q, SS, UV transmissibility). The coefficients (a, b, c, m) reflect sensitivity to UV and the degree of bacterial occlusion in solids. The EPA suggests default values for these coefficients for screening purposes ($a = 1.45 \times 10^{-5}$, $b = 1.30$, $c = 0.26$, $m = 1.96$), although it strongly recommends that they should be derived from direct pilot testing.

Some salient features of the above model include:

The equation is based on the ideal "log-death" mathematical relationship, as established from well known first order kinetics of inactivation. ($dN/dt = Kt$, where the inactivation constant, K, is represented in the EPA equation as $K = aI_{avg}^{b}$).

The model uses an average bulk-flow estimate of UV intensity (I_{avg}), calculated by a point source summation technique, incorporating effects of lamp type, system configuration, and wastewater transmissibility.

It also accounts for hydraulics, and the degree to which a system approaches plug-flow behavior, which is essential for effective UV disinfection. A dispersion coefficient (E) is used to quantify deviation of residence time distribution (RTD)

> from ideal plug-flow. The incorporation of this parameter allows a direct comparison of systems with significantly different flow configurations.
>
> Solids occlusion phenomenon is quantified by relating the residual indicator organism population contained in particulates (N_p) to the suspended solids content of the wastewater (SS), by an empirical relationship ($N_p = cSS^m$). (EPA, 1986:185)

This equation allows for correlation of pilot data for multiple systems into a single empirical relationship, determining values for the constants. Once calibrated using pilot data, the equation can be applied to the design of full-scale disinfection systems, taking into account the differences between the pilot and full-scale system characteristics, including the flow rate, number of lamp banks in series and expected dispersion.

For the purposes of this research, a spreadsheet will be developed and random numbers generated for the following values: N_o, u, x, E, I_{avg}, and SS. The numbers will be generated using a discrete distribution, since all values have an equally likely chance of occurring, with the range of numbers being determined from literature on pilot and full scale system studies (See Table 5). The reason for using randomly generated numbers is to demonstrate the viability of UV as a disinfection alternative to be used by various wastewater treatment plants for a variety of effluent characteristics. The value for the effluent coliform level (N) is chosen to be 200 cfu/100ml, which is a typical permit requirement for WWTP's to achieve. The model will show that for various wastewater parameters, UV disinfection is a viable alternative to the use of chlorine.

Table 5. Max and Min Values for UV Model

Parameters	Minimum	Maximum
N_o	100,000 cfu/100ml	2,000,000 cfu/100ml
u	0 cm/s	30 cm/s
x	0 cm	600 cm
E	0 cm^2/s	90 cm^2/s
I_{avg}	0 $\mu W/\ cm^2$	8000 $\mu W/\ cm^2$
SS	0 mg/l	35 mg/l

Preliminary Design of an Ozone System

The first step in designing an ozone disinfection system, is to determine the transferred ozone dosage, applied ozone dosage, and ozone production design values (EPA, 1986:147). To determine the transferred ozone dosage (T), we use the following equation, as developed by the EPA:

$$T = q * 10^{[Log(N/No)]/n}$$

where:

T = transferred ozone dosage (mg/l)
q = initial ozone demand (mg/l)
n = slope of the dose/response curve
N = effluent coliform concentration (#/100ml)
N_o = influent coliform concentration (#/100ml)

Transferred ozone dosage is used for establishing the relationship between ozone dosage and disinfection performance. Transferred ozone dosage required to achieve disinfection is dependent upon the quality of the wastewater, the plant discharge criteria, and the disinfection performance capability of the ozone contact basin (EPA, 1986:140). "Because of the variables involved, selection of transferred ozone dosage is probably the most difficult process design consideration" (EPA, 1986:140). The preferred method of calculating T is to perform pilot plant evaluation on the treated wastewater to be disinfected. Due to the limitations of this research, published data and/or existing full-scale plant operating data will be used; however, the reader is reminded that these data are site specific and may not be directly applicable to other installations. Stover found that to meet a stringent standard of 2.2 total coliforms per 100 ml, a transferred ozone dosage between 36 and 42 mg/l was required when secondary treatment plant effluent was disinfected (Stover, 1981:1642).

The initial ozone demand (q), will increase as the quality of the wastewater deteriorates (See Figure 11). Factors that affect the initial ozone demand include: organic and inorganic materials in the wastewater that are readily oxidized by ozone, such as iron, nitrite nitrogen, and manganese; materials that affect the COD concentration; and other materials (EPA, 1986:142). There is limited data available to allow quantification of the ozone demand for a particular wastewater; however, some general trends have been identified by the EPA based on wastewater COD concentration (See Table 6).

Table 6. Initial Ozone Demand Based on COD Concentration

COD Concentration		Initial Ozone Demand (q)
Low COD	20 - 30 mg/l	0.5 - 1.0 mg/l
Moderate COD	30 - 40 mg/l	1.0 - 2.0 mg/l
High COD	74 mg/l	5 mg/l

(EPA, 1986:142)

The dose/response curve is the plot of transferred ozone dose versus the coliform log survival and the slope of the curve represents the change in coliform survival per mg/l transferred ozone dosage. Pilot studies have shown that the slope of the dose/response curve (n) can vary from -2.51 to -6.65 (EPA, 1986:143)(See Figure 12).

Once T is calculated we must determine the applied ozone dosage (D) from the following equation:

$$D = T * \frac{100}{TE}$$

where:

TE = transfer efficiency

The transfer efficiency of ozone is influenced by the physical characteristics of the contactor and the quality of the wastewater. For a specified ozone dosage, wastewater of poor quality will have a high ozone demand and the contactor will exhibit a high TE. This high TE is due to the disappearance of ozone in oxidation reactions (EPA, 1986:132). See Figure 13 for an example of the effect of water quality on TE.

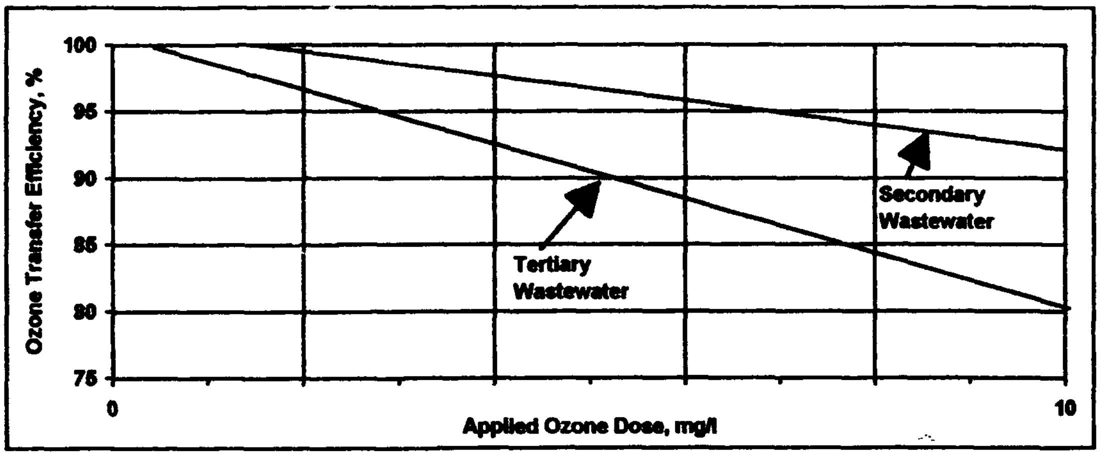

Figure 11. Ozone transfer efficiency decreases as applied ozone dosage increases and as ozone demand of the wastewater decreases. (Adapted from EPA, 1986:132)

The chemical quality of the wastewater also affects the TE of ozone, particularly pH and alkalinity. A high pH and/or a low alkalinity will cause a lower ozone residual because the hydroxyl radicals will be maximized. The lower residual will increase the exchange potential, or driving force, and will increase TE (EPA, 1986:132). Following is a summary of the important water quality considerations on ozone TE design:

a) Ozone TE will decrease as applied ozone dosage increases. A specified minimum design TE should be coupled with a specified applied ozone dosage.

b) Ozone TE will increase as wastewater quality deteriorates (i.e., ozone demand increases). A specified minimum design TE should be coupled with a specified description of the wastewater quality.

c) Ozone TE will increase as wastewater chemical quality favors the presence of hydroxyl radicals such as a high pH or low alkalinity. A comparison of TE of existing full-scale and pilot-scale results should consider differences in wastewater chemical quality. (EPA, 1986:132)

The production rate (P) is determined from is

determined from the following equation:

$$P = D * L * 8.34$$

where:

L = wastewater flow (mgd)

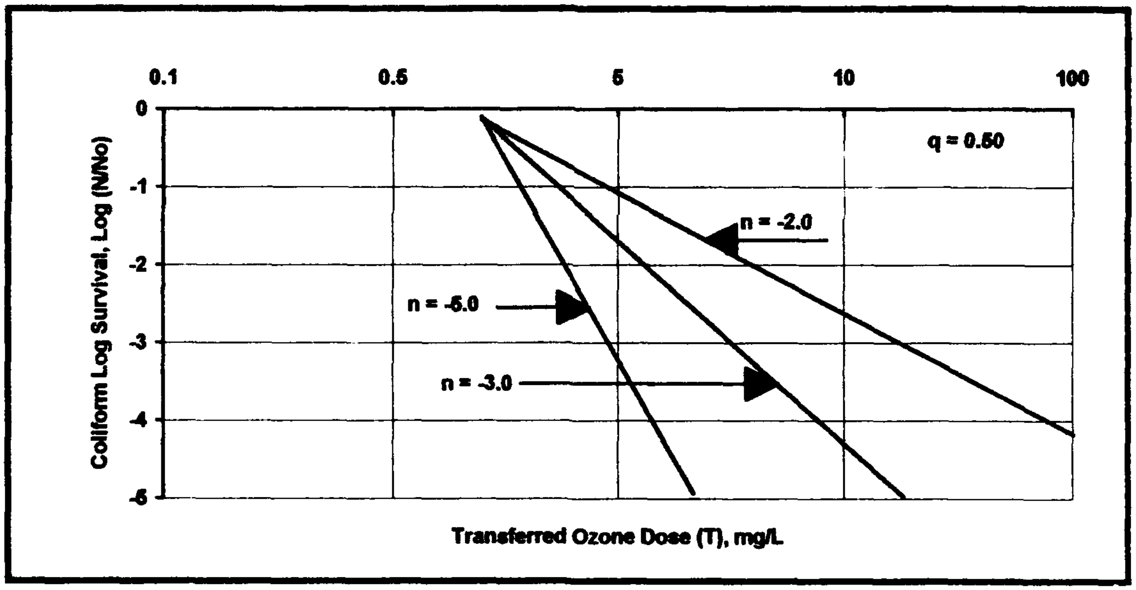

Figure 12. Example curve showing the effect of different slopes on transferred ozone dosage requirement.
(Adapted from EPA, 1986:143)

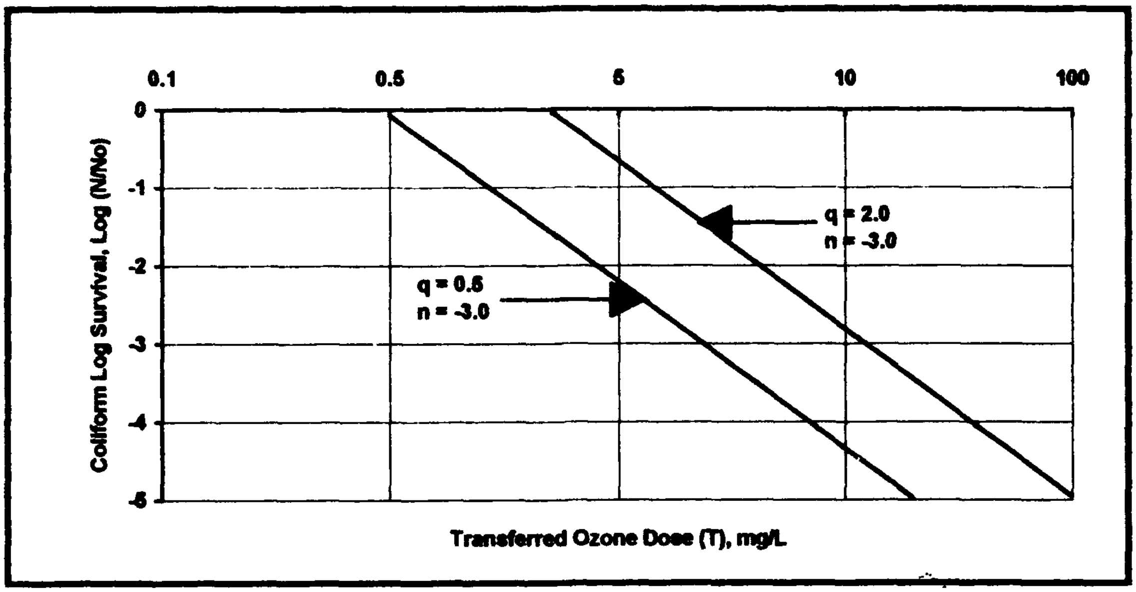

Figure 13. Example Curve showing the effect of different X-axis intercepts on transferred ozone dosage requirement. (Adapted from EPA, 1986:143)

Once P is determined for a variety of conditions, such as, varying N_o, N, L, n, and q, the design ozone production rate can be determined and subsequently the remaining parameters for the disinfection system. The reader is refereed to the EPA Design Manual for Municipal Wastewater Disinfection, for examples and procedures of carrying out a full scale preliminary design of an ozone disinfection system (EPA,1986).

The disinfection efficiency of ozone can be related to the amount of ozone transferred into the process water regardless of the contactor type (Venosa, 1983:462). Venosa developed an empirical model of a previously developed model by Given and Smith that indicates the effluent coliform numbers with respect to the amount of ozone transferred and the total chemical oxygen demand (TCOD) of the effluent (Venosa, 1983:462). The model is as follows:

$$\log_{10} TC = 4.38 - 4.58 \log_{10} T + 0.040\, TCOD$$

where

TC = total coliforms/100 ml

The model was validated on six different municipal effluents and the results closely predicted final coliform densities in five out of six of the effluents (WPCFm 1984:33). The one to which it was not applicable had a high concentration of industrial wastes that imposed substantially different demand requirements on the ozonation system (Venosa, 1983:462). There are restrictive assumptions that must be used in the application of the model as follows:

- Ozone is generated from pure oxygen;
- The gas-to-liquid flow ratio ($Q_G:Q_L$) is ≤ 0.44;
- A bubble diffuser contactor is used and operated in a countercurrent flow configuration; and
- Dose is varied by changing the power input to the generator while maintaining a constant $Q_G:Q_L$.

This model will be used in this research using a range for TCOD of 0 to 100 and a range for T of 5 to 100.

Determining Dechlorination Requirements

The EPA Design Manual for Municipal Wastewater Disinfection provides detailed examples for designing chlorination systems. The aim of this section is to provide a simplistic method for determining the amount of sulfur dioxide required to accomplish dechlorination. The reader is reminded that this method is intended as a basic method for determination and that before any decisions are made, a detailed determination should be accomplished.

The reaction between sulfur dioxide and free chlorine shows that one mole of sulfur dioxide reacts with one mole of either free chlorine or monochloramine through the following stoichimometric equations (EPA, 1986:48):

$$SO_2 + H_2O + HOCl = 3H^+ + Cl^- + SO_4^{-2}$$

$$SO_2 + 2H_2O + NH_2Cl = NH_4^+ + 2H^+ + Cl^- + SO_4^{-2}$$

In practical terms approximately 1 gram of sulfur dioxide is required per gram of chlorine. The reaction between chlorine and sulfur IV compounds is relatively rapid. Because of this rapid reaction there is typically no need for separate contact chambers for chlorination and dechlorination, the effluent pipe may be sufficient to allow for proper dechlorination. The piping and materials used for a chlorine system are satisfactory for use in a sulfur dioxide system, however, the systems used for chlorine must not be used for sulfur dioxide, or vice versa, prior to thorough cleaning, to prevent potentially explosive reactions from occurring (EPA, 1986:76). Controlling the sulfur dioxide dechlorination system is more difficult than a chlorination system due to the varying chlorine residuals leaving the chlorine contact chamber. To determine the amount of sulfur dioxide required for dechlorination, take the average chlorine residual of the effluent and determine the yearly requirement for sulfur dioxide. For example, a chlorine residual of 1.3 mg/l would require:

*365 days/year * 1.2 MGD * 1.3 mg/l * 8.34 lbs/gal ≈ 4,800 lb/yr or 2.4 tons/year*

"The estimation of chlorination and dechlorination costs is highly site specific" (EPA, 1986:80). Some considerations include:

- the use of the need for separate chlorine contact basins versus the use of the effluent channel as a contactor,
- site-specific chemical costs, and
- required chlorine dosages (EPA, 1986:80)

Preliminary rough estimates of alternatives can be developed from available literature data based on field experience, particularly other Air Force Installations using sulfur dioxide dechlorination (See Appendix A).

Proof of Concept

The concept of selecting a disinfection alternative is well documented in the EPA Design Manual for Municipal Wastewater Disinfection. The tables in Chapter 3 outline the process of determining the requirements and provide guidance for selecting a disinfection method. With the impending revision of the CWA, it is conceivable that WWTP's will be required to minimize or eliminate the use of chlorine.

Verification and Validation

All the equations, figures, and graphs that have been presented were obtained from documented literature. To ensure that the equations were properly input into the MS Excel Spreadsheets, actual data obtained from WWTP's was used, the remaining data was taken from the EPA Design Manual.

The design model equation was verified using the following data:

Table 7. Validation of UV Model Equation

Actual Data (Fairborn WWTP)		Assumptions (EPA Design Manual)	
N_o	7600 cfu/100ml	u	12 cm/s
x	457 cm	E	75.00 cm^2/s
I_{avg} (at 70% transmittance)	8000 $\mu W/cm^2$	a	$1.45*10^{-5}$
Suspended Solids	9 mg/l	b	1.30
		c	0.26
		m	1.96

The above data, when input into the UV Design Model Equation, resulted in a total coliform reading of 19 cfu/100ml. The Fairborn WWTP laboratory determined the fecal coliform reading to be 1 cfu/100ml. These results demonstrate the validity of the model equation and the parameters utilized, since a fecal level of 1 is typical for a total coliform level of 19.

Summary

The methodology outlined in this chapter was adapted primarily from EPA guidance. The flow charts and graphs provide a sound background for basing a preliminary decision on selecting a disinfection method. The model equations presented also allow the users to base a decision dependent upon the current treatment efficiency of their WWTP. The methodology presented here is intended only to be utilized as a preliminary screening tool and the need for performing pilot studies cannot be overemphasized.

IV. Results and Findings

Overview

This chapter presents the findings from the UV and Ozone model equations introduced Chapter 3, along with the results of following the tables for choosing a disinfection option. Calculations were performed using MS Excel spreadsheet and the variables of the model equations were chosen within the ranges of values reported in the literature. These findings are preliminary and are made without performing in-depth pilot studies.

Results of Model Manipulation

The UV model equation as presented in Chapter 3 is as follows:

$$N = N_o \exp \left[ux/2E \left\{1 - \left(1 + 4E\, a I_{avg}{}^{b}/u^2\right)^{1/2}\right\}\right] + cSS^m$$

The following parameters were considered constant throughout each run:

$$\begin{aligned} a &= 1.45 \times 10^{-5} \\ b &= 1.30 \\ c &= 0.26 \\ m &= 1.96 \end{aligned}$$

Figure 14 shows the effect of varying the dispersion coefficient, E, from 0 to 90 cm^2/s while assigning the following values to the remaining variables:

N = 200 CFU/100ml
N_o = 2,000,000 CFU/100ml
u = 16 cm/s
x = 450 cm
I_{avg} = 7000 $\mu W/cm^2$
SS = 15 mg/l

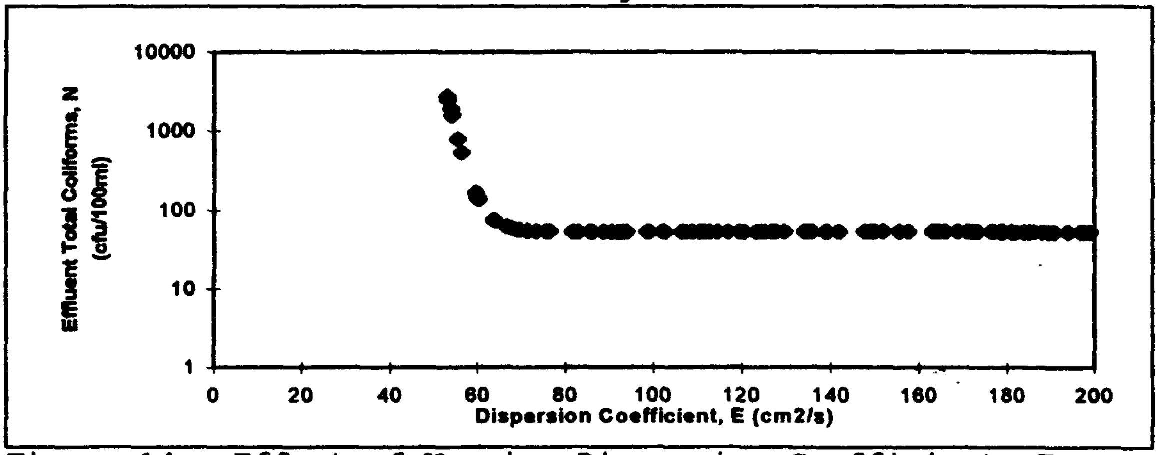

Figure 14. Effect of Varying Dispersion Coefficient, E.

These values were selected based on typical WWTP operating data provided in the EPA Design Manual for Municipal Wastewater Disinfection. The graph shows that for values of E greater than 60 cm^2/s, the effluent total coliform remains below the desired 200 CFU/100ml level.

Varying the influent total coliform level, N_o, from 100,000 to 2,000,000 CFU/100ml while assigning the following values to the remaining variables listed below, showed no change in the effluent total coliform levels.

N = 200 CFU/100ml
u = 16 cm/s
x = 450 cm
E = 75 cm^2/s
I_{avg} = 7000 $\mu W/cm^2$
SS = 15 mg/l

The model demonstrated that for values of N_o, from 100,000 to 2,000,000 CFU/100ml the effluent total coliform remains constant at 53 CFU/100ml level. (See data generation in Appendix B).

Figure 15 shows the effect of varying the suspended solids level, SS, from 0 to 35 mg/l while assigning the following values to the remaining variables:

$$N = 200 \text{ CFU/100ml}$$
$$N_o = 2{,}000{,}000 \text{ CFU/100ml}$$
$$u = 16 \text{ cm/s}$$
$$x = 450 \text{ cm}$$
$$E = 75 \text{ cm}^2\text{/s}$$
$$I_{avg} = 7000\ \mu\text{W/cm}^2$$

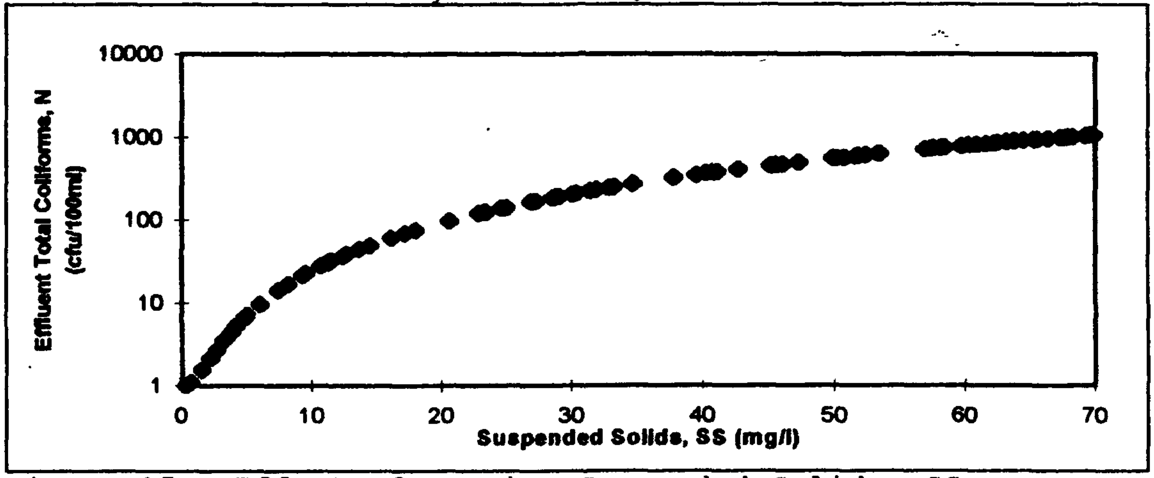

Figure 15. Effect of Varying Suspended Solids, SS.

These values were selected based on typical WWTP operating data provided in the EPA Design Manual for Municipal Wastewater Disinfection. The graph shows that for values of SS, from 0 to 70 mg/l, the effluent total coliform does not exceed the desired 200 CFU/100ml until the suspended solids level reaches 30 mg/l.

Figure 16 shows the effect of varying the velocity of the effluent u, through the reactor, from 0 to 30 cm/s while assigning the following values to the remaining variables:

$$
\begin{aligned}
N &= 200 \text{ CFU/100ml} \\
N_o &= 2{,}000{,}000 \text{ CFU/100ml} \\
x &= 450 \text{ cm} \\
E &= 75 \text{ cm}^2/\text{s} \\
I_{avg} &= 7000\ \mu\text{W/cm}^2 \\
SS &= 15 \text{ mg/l}
\end{aligned}
$$

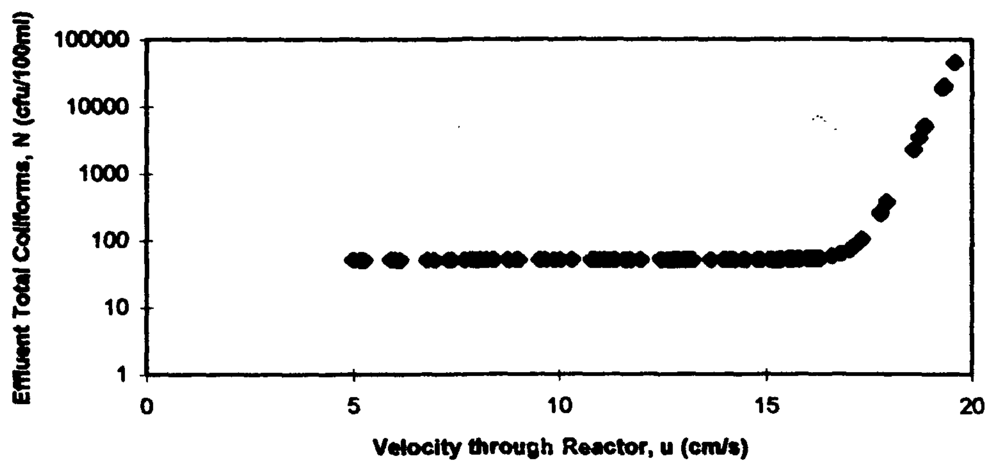

Figure 16. Effect of Varying Velocity, u.

These values were selected based on typical WWTP operating data provided in the EPA Design Manual for Municipal Wastewater Disinfection. The graph shows that for values of u, from 0 to 20 cm/s, the effluent total coliform does not exceed the desired 200 CFU/100ml until the velocity reaches 18 cm/s, then the effect is very dramatic.

Figure 17 shows the effect of varying the reactor length, x, from 0 to 600 cm while assigning the following values to the remaining variables:

$$
\begin{aligned}
N &= 200 \text{ CFU/100ml} \\
N_o &= 2{,}000{,}000 \text{ CFU/100ml} \\
u &= 16 \text{ cm/s} \\
E &= 75 \text{ cm}^2\text{/s} \\
I_{avg} &= 7000\ \mu\text{W/cm}^2 \\
SS &= 15 \text{ mg/l}
\end{aligned}
$$

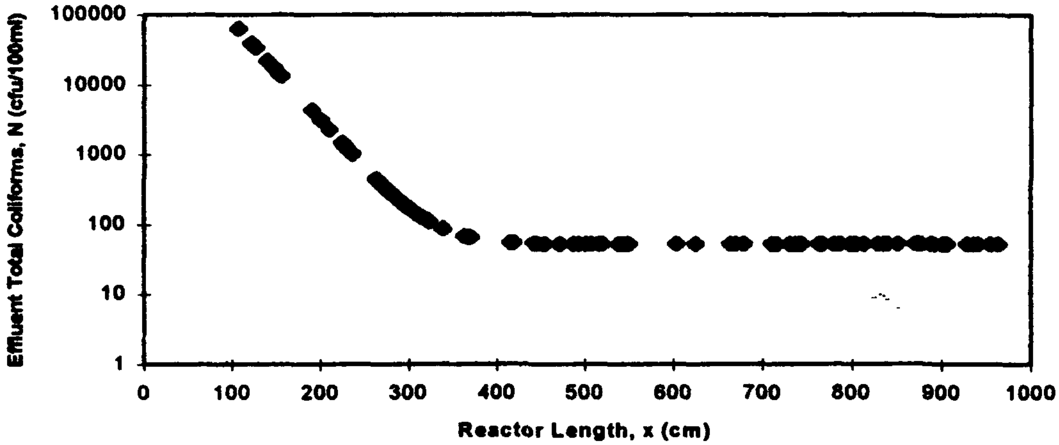

Figure 17. Effect of Varying Reactor Length, x.

These values were selected based on typical WWTP operating data provided in the EPA Design Manual for Municipal Wastewater Disinfection. The graph shows that above 350 cm, the length of the reactor does not affect the effluent total coliform. At lengths below 290 cm, however, the variation of effluent total coliforms with reactor length is very dramatic.

Figure 18 shows the effect of varying the average reactor intensity, I_{avg}, from 0 to 8000 μW/cm^2 while assigning the following values to the remaining variables:

$N = 200$ CFU/100ml
$N_o = 2{,}000{,}000$ CFU/100ml
$u = 16$ cm/s
$x = 450$ cm
$E = 75$ cm^2/s
$SS = 15$ mg/l

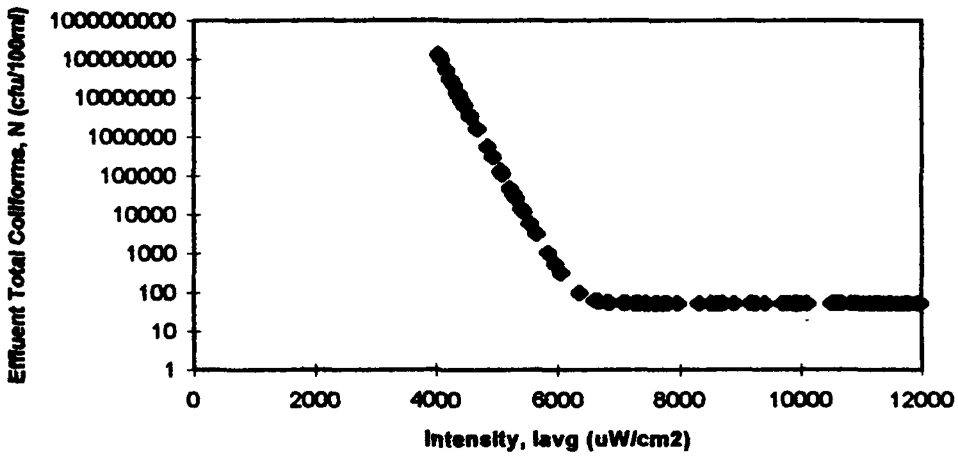

Figure 18. Effect of Varying Intensity, I_{avg}.

These values were selected based on typical WWTP operating data provided in the EPA Design Manual for Municipal Wastewater Disinfection. The graph shows that for values of I_{avg}, greater than 6000 µW/cm^2, the effluent total coliform does not exceed the desired 200 CFU/100ml. For values of below 6000 µW/cm^2, the effluent total coliforms change very drastically.

The Ozone model equation demonstrating ozone disinfection efficiency:

$$\log_{10} TC = 4.38 - 4.58 \log_{10} T + 0.040\, TCOD$$

was input into the spreadsheet and values were selected for T and TCOD as follows:

T = 1, 5, 10, 15, 20, 25, 30, 35, and 40 mg/l
TCOD = 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 mg/l

Figure 19 shows the effect that varying these variables has on the effluent total coliform levels. The graph shows that as TCOD increases, the level of transferred ozone dose must be increased to attain an effluent total coliform level below 200 cfu/100ml. For example, at a TCOD level of 10 mg/l and a transferred ozone dose of 5 mg/l, we obtain a effluent total coliform level of 38 cfu/100ml. As compared to a TCOD level of 100 mg/l and transferred ozone dose of 5 mg/l, which yields an effluent total coliform level of 151,000 cfu/100ml.

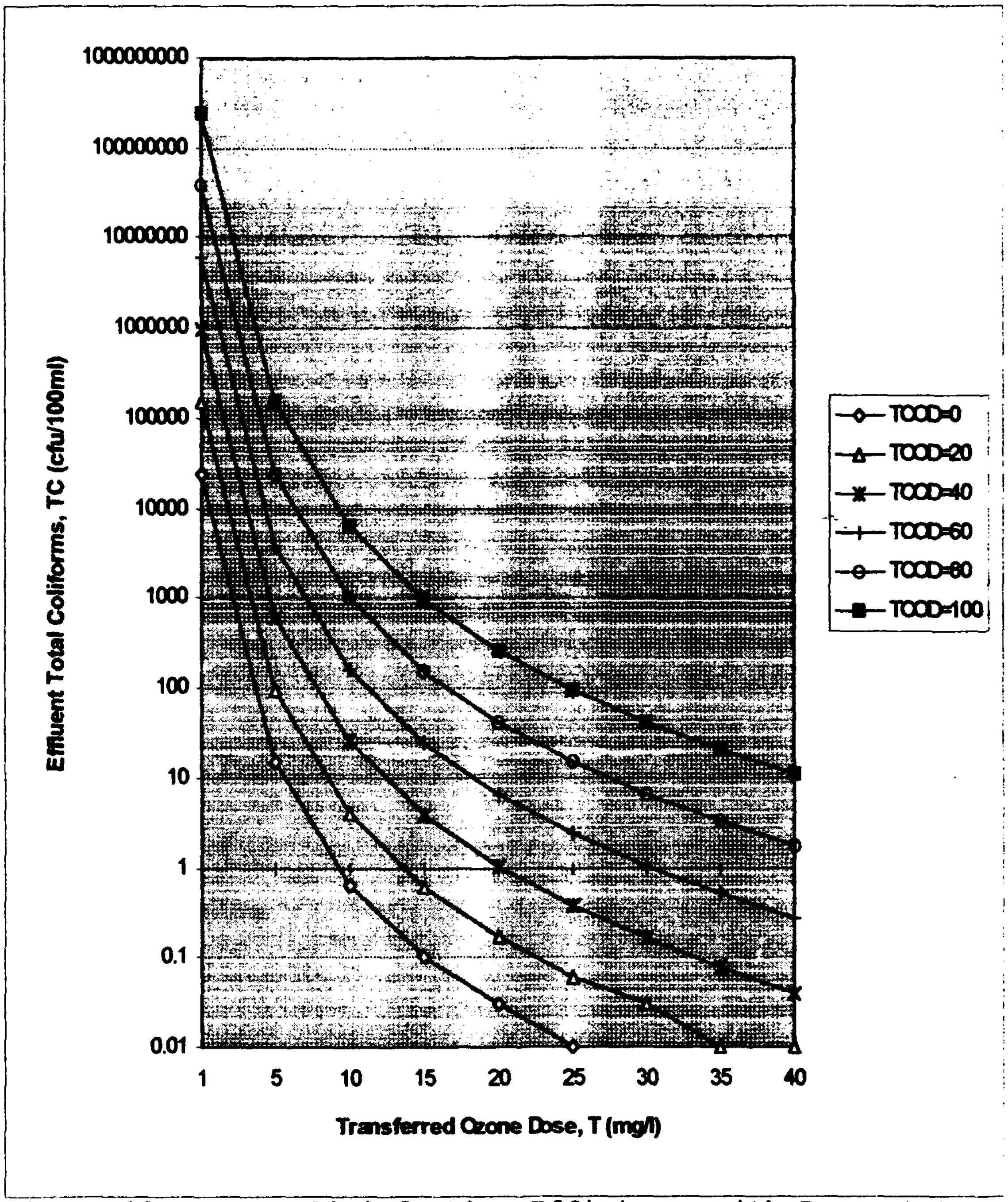

Figure 19. Ozone Disinfection Efficiency with Respect to TCOD and the Transferred Ozone Dose.

In testing the methodology presented against the data obtained in the survey, Columbus AFB, Mississippi was selected as an example installation. For the purposes of following the methodology of Choosing an Alternative Disinfection Method/Option presented in Chapter 3, the following assumptions were made:

1) The receiving body of water is used for primary contact recreation,
2) There is a potential for significant chlorine induced toxicity to aquatic life.
3) The regulatory agency has directed the installation to eliminate any chlorine residual and to minimize the use of chlorine.

Based upon the data received from Columbus AFB, (See Appendix A), and applying it to Table 3, Ultraviolet Disinfection is the most suitable alternative, based on the following factors:

1) The plant is considered small at 1.0 MGD;
2) UV technology is not complex;
3) UV is very safe;
4) UV is non-toxic to aquatic life;
5) UV is not affected by pH;
6) UV is non-corrosive; and
7) O&M sensitivity is only moderate.

UV disinfection systems can be retrofit to existing chlorine contact chambers with minor modifications that may include the installation of weirs to regulate flow. Based on data in Appendix C, one 40 lamp module would be required, however, two would be desired for the purposes of backup capabilities. Based on the graph in Figure 10, approximately 18 mandays in yearly labor requirements would be required to maintain the system. No data was available for the labor requirements for maintaining a chlorine or ozone disinfection system.

Dechlorination could also be an option, however, it involves the use of more chemicals, increases dissolved solids, is pH dependent, is corrosive, and introduces additional safety concerns.

Evaluation of Study Objectives

The objective of this research was to review the current state of knowledge of various methods of wastewater disinfection, survey the Air Force WWTPs, and develop a decision making aid for selecting an alternative method of disinfecting wastewater.

There has been and continues to be a great deal of research accomplished on the alternative methods of wastewater disinfection. With advances in technology, UV disinfection is emerging as the method of choice for small domestic WWTPs. The Air Force WWTPs primarily employ chlorine for the purposes of disinfection and the data obtained from the survey demonstrates that the majority of these plants could conceivably employ UV disinfection. This document provides the necessary information for making a preliminary decision on selecting a disinfection method should it ever become necessary or mandatory to cease the use of chlorine.

Summary

This chapter provided the results of the model equation manipulations. Ranges for typical wastewater effluent characteristics have been determined and provide aid in determining a viable option to the use of chlorine for disinfection. The need for in-depth pilot studies is again emphasized since the factors that affect efficient disinfection vary from treatment plant to treatment plant.

V. Conclusions and Recommendations

Overview

This chapter summarizes the research accomplished, explains the conclusions drawn from the research, and makes recommendations for further research in the area of alternative methods of wastewater disinfection. The conclusions drawn here are solely the views of this author and are based on the research conducted, site visits, and telephone conversations.

Summary of Research

The research was conducted utilizing the publications listed in the bibliography, as well as numerous others not cited here. The general issue researched was the potential need for alternative wastewater disinfection methods due to the possible restrictions or banning of chlorine use. The Air Force owns and operates numerous WWTPs, with the majority of these plants employing a chlorine disinfection system (See Appendix B).

The research centered around the following disinfection methods: chlorination/dechlorination, ultraviolet disinfection, and ozonation. These disinfection systems are the most widely employed at WWTPs. Guidance for selecting an alternative disinfection method was obtained from the EPA Design Manual for Municipal Wastewater Disinfection. Model equations for ultraviolet and ozone disinfection were input into MS Excel Spreadsheets and, when possible, actual parameters from representative WWTPs were employed. When the parameters were not available, the values were generated within the parameters established by the EPA and other research. Site visits were accomplished to establish familiarity with UV and ozone disinfection systems as well as to obtain WWTP operators satisfaction or dissatisfaction with the particular system. Cost data is presented in Appendix C, and was obtained from various vendors. The costs presented are estimates and are not intended for use as quotes should a particular system be chosen.

Research Conclusions

1) UV disinfection systems are the most viable alternative with respect to the size and type of WWTP utilized at Air Force Installations.

2) Ozone and dechlorination systems are viable alternatives, however, the controls required and the hazardous nature of the chemicals involved due not justify there use by the Air Force.

3) UV disinfection pilot studies should be performed at Air Force WWTPs and the installation of UV systems should be pursued if the results of the pilot studies are favorable.

Although each of the disinfection systems that were researched are viable and proven effective, Ultraviolet Disinfection appears to be the best alternative for the size, type, and capability of wastewater treatment plant that the Air Force operates.

Ozone is highly effective in disinfecting wastewaters of an industrial nature and viable for medium to large plants, where purified oxygen is readily available or can be generated on-site. Ozone, like chlorine, is hazardous and poses a danger to operators and surrounding neighbors. Each requires stringent safety precautions and training; however, properly operated, the systems may perform without incident.

Dechlorination systems do not eliminate the need for the handling and storage of hazardous chemicals. The controls for dechlorination requires significant operator interface.

Ultraviolet disinfection has evolved into a virtually operator free system, that requires only minor day-to-day operator interface and maintenance. The results of the survey demonstrate that the majority of the Air Force's WWTPs are currently operating within the required parameters to make UV disinfection viable and efficient. UV disinfection systems can be retrofitted into existing chlorine contact chambers or modular open-channel systems can be installed, both requiring little space.

UV disinfection poses only minor hazards and is easily automated to assure efficient operation. The Fairborn WWTP had utilized a chlorination system and had plans to install a dechlorination system. These plans were changed and the current UV system was installed. The personnel at the plant are extremely pleased with the efficiency of the system and ease of operation and maintenance. The personnel at the Fairborn plant have not noticed an appreciable increase in power consumption for the plant, which might be expected when installing a UV system.

UV disinfection is growing in popularity and technological advancements are minimizing the time that had been devoted to the operation of chlorination systems. Chlorination systems have typically been set at a feed rate and left alone, UV uses photocells and flowmeters to control the amount of disinfection required and daily checks of the operator interface is all that is typically required.

UV disinfection warrants a serious review if the Air Force deems it necessary to upgrade or alter operations with respect to disinfection at any of its WWTPs.

Recommendations for Further Research

- Perform a UV disinfection pilot study at an Air Force WWTP

- Develop a computer model that enhances the charts, figures, and spreadsheets used in this research

Appendix A: Questionnaire and Current List of Air Force Wastewater Treatment Plants

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

MEMORANDUM FOR ENVIRONMENTAL FLIGHTS (see distribution)
ATTENTION: Compliance Managers

FROM: AFIT/ENV
Box 4366
2950 P Street
Wright Patterson AFB OH 45433-7765

SUBJECT: Collection of Environmental Compliance Data

1. The Air Force Institute of Technology is in a unique position to address many of the challenges facing today's Air Force. One such challenge is the Air Force's goal to reach total environmental compliance. Capt David Piech, who is presently enrolled in AFIT's Engineering and Environmental Management masters degree program, is researching alternative methods of disinfecting effluent from wastewater treatment plants (WWTP).

2. Capt Piech's research is directed toward comparing the alternatives available to the chlorination of effluent from Air Force WWTPs. He is attempting to develop a decision making tool that can be used to select the most cost effective and efficient method of disinfecting WWTP effluents. To do this, he needs some data that is not tracked by your MAJCOM which addresses your base's treatment of wastewater. This promising research could provide an outline for selecting an alternative to the use of chlorine for the disinfection of WWTP effluent.

3. Attached is a questionnaire pertaining to specific operations and limitations for the operation of WWTPs. Please fill out this data sheet and return it to Capt Piech at the above address or fax it to him at DSN 986-7302 by 6 May 94. We greatly appreciate your assistance with this research effort. You are participating in a critical step of an effort that will pay great dividends in the Air Force's future.

Michael L. Shelley, Lt Col, USAF, BSC
Head, Department of Engineering and
Environmental Management

Attachment:
WWTP Data Sheet

DISTRIBUTION:
See Attached

Name of Installation____.

Name and Position of Individual Completing this Questionnaire________________

____.

DSN________________________.

Does your installation operate a wastewater treatment plant? Yes No
(If No please stop here and return questionnaire.)

Type of treatment plant (i.e. Primary, Secondary etc.)____________________

Please briefly describe plant operations.______________________________

____

____

____

____.

Method of disinfection (i.e. Chlorination, Ozone, Ultra Violet)____________.

If Chlorination, do you dechlorinate? Yes No

If yes, what method is used?____.

Average Amount of Chlorine Used Per Day____________________________.

Maximum Design Flow____.

Average Daily Flow____.

Continued on Next Page...

	Permit Limitations	**Monthly Average**
Total Coliforms	________	________
Suspended Solids	________	________
Ammonia-Nitrogen	________	________
Turbidity	________	________
Chlorine Residual	________	________
BOD	________	________

Effluent is discharged to________________________________.
(i.e. River, Stream, etc. and Specific Name of Receiving Body)

Has your WWTP ever experienced a trihalomethane problem with the effluent or the receiving body that the effluent is discharged to?________________.

(If so, please briefly explain)________________________________

____

____.

Please add any specific requirements or operations pertaining to disinfection that are enforced by a regulatory agency.

Major Gene Csaszar
or Incumbent
89 SPTG/CEV
Stop 34
Andrews AFB, D.C. 20331-5000

Bill Hanson
or Incumbent
3 SPTG/CEV
22040 Maple Street
Elmendorf AFB, AK 99506-3240

William Dunne
or Incumbent
AEDC/CEV
100 Kindel Dr Sutie B-314
Arnold AFB, TN 37389

Greg Miller
or Incumbent
9 CES/CEV
6451 B Street
Beale AFB, CA 95903-1708

Bruce Oshita
or Incumbent
27 CES/CEV
111 Engineers Way
Cannon AFB, NM 88103-5136

Robert Turnage
or Incumbent
14 CES/CEV
555 Simler Boulevard, Suite 114
Columbus AFB, MS 39710-6010

John Avolio, Jr.
or Incumbent
AFFTC/EM
70 North Wolfe Ave.
Edwards AFB, CA 93524-6225

Capt Max Gandy
or Incumbent
354 CES/CEV
2258 Central Ave., Suite 1
Eglin AFB, FL 32542-5133

Kate Siftar
or Incumbent
354 CES/CEVC
2258 Central Ave, Ste 1
Eielson AFB, AK 99702-2225

David L'Esperance
or Incumbent
28 SG/CEV
2372 Westover Ave.
Ellsworth AFB, SD 57706-4700

William Rattenborg
or Incumbent
50 CES/CEV
500 Sunnyvale Street
Falcon AFB, CO 80912-5019

Wayne Koop
or Incumbent
319 CES/CEV
460 Steen Blvd
Grand Forks AFB, ND 58205-6231

Jeff Woodring
or Incumbent
305 SPTG/CEV
Grissom AFB, IN 46971

Roger N. Wilkinson
or Incumbent
49 CES/CEV
550 Tabosa Ave.
Holloman AFB, NM 88330-8458

Michael G. Gold
or Incumbent
16 SPTG/CEV
415 Independence Road
Hurlburt Field, FL 32544-5000

Gary R. Koski
or Incumbent
410 CES/CEV
400 Cave, Suite 100
K.I. Sawyer AFB, MI 48943-3200

Monica Fields
or Incumbent
251 CES/DEV
251 4th Street
Laughlin AFB, TX 78843-5143

Capt Michael T. Ray
or Incumbent
58 CES/CEV
7383 N Litchfield Road
Luke AFB, AZ 85309-1526

Vicki T. Fisher
or Incumbent
6 CES/CEV
8011 Hangar Row Dr Ste 3
MacDill AFB, FL 33608-5000

Dr. L.J. Watson
22 CES/CEV
March AFB, CA 92518-5000

Martin Eisenhart
or Incumbent
438 SPTG/CEV
3400 Broidy Rd.
McGuire AFB, NJ 08641-5303

Tom Atkinson
or Incumbent
5 CES/CEV
410 Summit Dr Unit 1
Minot AFB, ND 58705-5006

Carlton Crenshaw, Jr.
or Incumbent
347 CES/CEV
3485 Georgia Street
Moody AFB, GA 31699-1707

John Hale
or Incumbent
366 SG/CEV
1100 Liberator St., Bldg.1297
Mt. Home AFB, ID 83648-5426

Olin Miller
or Incumbent
45 CES/CEV
1229 Jupiter Street
Patrick AFB, FL 32925-3343

Capt Sherry Brown
or Incumbent
64 CES/CEV
Reese AFB, TX 79489-5000

Travis Wayne Fowler
or Incumbent
82 CES/CEV
Sheppard Training Center
Sheppard AFB, TX 76311-5000

Shawn Politino
or Incumbent
WR-ALC/EMC
216 Ocmulgee Ct
Robins AFB, GA 31098-1646

Major Anthony F. DeSimone
or Incumbent
375 AW/EMO
701 hangar Road
Scott AFB, IL 62225-5035

R. Marshall Dixon
or Incumbent
363 CES/CEV
427 Chapin St.
Shaw AFB, SC 29152-5123

Allen K. Lawrence
or Incumbent
OC-ALC/EM
8745 Entrance Rd A
Tinker AFB, OK 73145-3001

Traci Tucker Schell
or Incumbent
325 SG/CEV
119 Alabama Avenue
Tyndall AFB, FL 32403-5014

Gene Gallogly
or Incumbent
USAFA/CEV
8120 Edgerton Drive
U.S. Air Force Academy, CO 80840-2400

Capt Eric J. Wilbur
or Incumbent
351 CES/CEV
930 Arnold Ave
Whiteman AFB, MO 65305-5022

JUNE 93

Bases With On Base Sewage Treatment Plants

	Bases	Recent Activity
1.	Beale AFB CA	OMTAP 91
2.	Ellsworth AFB KS	Upgrade 93, OMTAP 93
3.	Grand Forks AFB	Upgrade 93
4.	March AFB CA	OMTAP 93, Proposed to Become Res or ANG Base
5.	Minot AFB ND	Upgrade 93
6.	Whiteman AFB MO	OMTAP, Upgrade/Expand
7.	Andrews AFB MD (4)	Replace/Upgrade/Connect
8.	Scott AFB IL	New Cl Contact Tank 93
9.	McGuire AFB NJ	New 93 - OMTAP
10.	Hurlburt Fld FL	New 93
11.	Holloman AFB NM	New 93/94
12.	Luke AFB AZ	Upgrade 92
13.	MacDill AFB FL	
14.	Moody AFB GA	OMTAP
15.	Mt Home AFB ID	WWTP Study (New 96)
16.	Shaw AFB NC	Upgrade 92
17.	Tyndall AFB FL	
18.	Cannon AFB NM	WWTP Study
19.	Tinker AFB OK	
20.	Robins AFB GA	Upgrade
21.	Eglin AFB FL (3)	
22.	Arnold AFB TN	
23.	Edwards AFB CA	New
24.	Laughlin AFB TX	
25.	Reese AFB TX	
26.	Columbus AFB MS	(New 96)
27.	Elmendorf AFB AK	
28.	Eielson AFB AK	Expand 95
29.	Shemya AFB AK	
30.	King Salmon AFS AK	
31.	Galena AFS AK	
32.	USAF Academy CO	Upgrade 94
33.	Cape Canaveral(Patrick AFB) FL	New 94
34.	Falcon AFS CO	
35.	New Boston AFS NH	Small
36.	Eldorado AFS TX	Small
37.	Volk Field ANGB MA	92 Upgrade
38.	McEntire ANGB SC	
39.	Otis ANGB MA	92 Upgrade
40.	Phelp-Collins ANGB MI	
41.	Schenectady ANGB NY	
42.	McGhee-Tyson ANGB TN	
43.	Martinsburg ANGB WV	
44.	Indian Springs Aux Fld, NV	Small
45.	Gila Bend Aux Fld AZ	Small
46.	Grissom AFB, IL	93 Upgrade, 94 to Res(Small)
47.	KI Sawyer, WI	95 Proposed Closure List
48.	Sheppard AFB, TX	95 Regional Connection Partially Connected Now

Post-it™ brand fax transmittal memo 7671 | # of pages ▸ 1
To CAPT DAVID AECH | From H.C. ANDERSON
Co. AFIT/ENV | Co. HQ AFCESA/ENC
Dept. BOX 4366 | Phone # DSN 523-6345
Fax # 986-9302 | Fax # 523-6219

AD-A284 786 EVALUATION OF ALTERNATIVE METHODS FOR WASTEWATER DISINFECTION(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING D C PIECH SEP 94 2/2

UNCLASSIFIED AFIT/GEE/ENV/94S-18 XC-AFIT NL

END
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Air Force Wastewater Treatment Plants

							Permit	Limitations				
	Treatment	Disinfection	Dechlorination	Chlorine	Max Design	Avg Daily	Total	Suspended	Amonia-			
Air Force Base	Type	Method	Method	Use/Day	Flow	Flow	Coliform	Solids	Nitrogen	Turbidity		
Arnold, TN	Secondary/TF	Cl		5lbs	0.232 MGD	0.5MGD	200	30mg/l				
Canon, NM	Secondary											
Columbus, MS	Secondary	Cl		35lbs	1.0 MGD	0.7 MGD	400	45 mg/l				
Ellsworth, SD	Secondary	Cl/deCl	Sulfur Dioxide	40 lbs	1.5 MGD	0.9 MGD	1000	30 mg/l				
Elmendorf, AK	Primary	Cl		6 lbs	.005 MGD	0.0041 MGD	43	70 mg/l				
Grand Forks, ND	No WWTP											
Holloman, NM	Faculative Lagoon											
Hurlburt Fld, FL	Primary	Cl	Sulfur Dioxide	30 lbs	1.0 MGD	0.522 MGD	200	5 ppm	3 ppm	2 NTUs		
K.I. Sawyer, MI	Tertiary	Cl/deCl	Sulfur Dioxide	25 lbs	3.0 MGD	0.75 MGD	200	30 mg/l	6 mg/l			
Luke, AZ	Tertiary	UV			1.2 MGD	0.4 MGD	4000	30 mg/l	0.02 mg/l			
March, CA	Secondary/TF	Cl		55 lbs	1.2 MGD	0.7 MGD	240	30mg/l				
McGuire, NJ	Third Stage	Cl	Sulfur Dioxide	50 lbs	1.25 MGD	1.2 MGD	200	30 mg/l	19 mg/l			
Minot, ND	Primary					0.888 MGD	400(7 day Avg)	45 mg/l				
Patrick, FL	Secondary	Cl/deCl	Sulfur Dioxide	55 lbs	1.0 MGD	0.6 MGD	200	20 mg/l		2 NTUs		
Reese, TX	Secondary	Cl		25 lbs	0.5 MGD	0.044 MGD	N/A	30 mg/l				
Shaw, SC	Secondary	Cl/deCl	Sulfur Dioxide	13 lbs	1.2 MGD	0.908 MGD	1000	30 mg/l	4 mg/l			
Tinker, OK	Sanitary-Secondary				0.7 MGD	0.4 MGD		25 mg/l				
USAFA, CO	Tertiary	Cl			4.5 MGD	1.6 MGD						

Air Force Wastewater Treatment Plants

			Monthly	Averages					Effluent
	Chlorine		Total	Suspended	Amonia-				Discharged
Air Force Base	Residual	BOD	Coliform	Solids	Nitrogen	Turbidity	Cl Residual	BOD	To:
Arnold, TN	0.5mg/l daily	30 mg/l	10	8 mg/l			0.4 mg/l daily	10 mg/l	Rowland Creek
Canon, NM				200 mg/l	15-38 mg/l			334 mg/l	Playa Lake
Columbus, MS	1.0 mg/l	45 mg/l	<10	12 mg/l			0.2 mg/l	7 mg/l	Tombigbee Waterway
Ellsworth, SD		30 mg/l	20	27 mg/l				12 mg/l	Box Elder Creek
Elmendorf, AK	ND	65 mg/l	14					45 mg/l	Cook Inlet
Grand Forks, ND									
Holloman, NM									Lake Holloman (Playa)
Hurlburt Fld, FL	0.1 mg/l deCl	5 mg/l							Wetlands
K.I. Sawyer, MI	0.05 mg/l daily	30 mg/l	3	11 mg/l	0.3 mg/l		0.00 mg/l	7 mg/l	Silver Lead Creek
Luke, AZ	0.05 ppm	30 mg/l	160	5 mg/l	11 mg/l	2 NTUs		5 mg/l	Aqua Fria Dry River Bed
March, CA		30 mg/l	<2	30 mg/l				30 mg/l	Irrigation Pond to Golf Course
McGuire, NJ	Inst. Max	30 mg/l	18	8.17 mg/l	12.33 mg/l		<0.1	13.92 mg/l	Crosswicks Creek
Minot, ND		45 mg/l							Egg Creek to Souris River
Patrick, FL	0.01 to river/1.0 to golf crse	20 mg/l	10	7.5 mg/l		1 NTU	0 to river/1.5 to golf crse	5 mg/l	Banana River
Reese, TX	1.0 mg/l	30 mg/l		18 mg/l			1.2 mg/l	6 mg/l	Sewage Lake
Shaw, SC	<100 ug/l	15 mg/l	177	14 mg/l	0.16 mg/l		0.106 ug/l	9.3 mg/l	Beech Creek to Wateree River
Tinker, OK		15 mg/l		15 mg/l				10 mg/l	East Soldier Creek
USAFA, CO	0.003 mg/l		30	30 mg/l				30 mg/l	Irrigation Reservoirs

Appendix B: Data Generation for Model Equations

Effect of Varying Dispersion Coefficient E with all other parameters held constant

No	u	x	E	Iavg	SS	a	b	c	m		N
2000000	16	450	53	7000	15	1.45E-05	1.30	0.26	1.96	53	2760
2000000	16	450	53	7000	15	1.45E-05	1.30	0.26	1.96	53	2550
2000000	16	450	54	7000	15	1.45E-05	1.30	0.26	1.96	54	1911
2000000	16	450	54	7000	15	1.45E-05	1.30	0.26	1.96	54	1595
2000000	16	450	56	7000	15	1.45E-05	1.30	0.26	1.96	56	793
2000000	16	450	56	7000	15	1.45E-05	1.30	0.26	1.96	56	535
2000000	16	450	60	7000	15	1.45E-05	1.30	0.26	1.96	60	167
2000000	16	450	60	7000	15	1.45E-05	1.30	0.26	1.96	60	144
2000000	16	450	60	7000	15	1.45E-05	1.30	0.26	1.96	60	136
2000000	16	450	64	7000	15	1.45E-05	1.30	0.26	1.96	64	75
2000000	16	450	64	7000	15	1.45E-05	1.30	0.26	1.96	64	73
2000000	16	450	67	7000	15	1.45E-05	1.30	0.26	1.96	67	61
2000000	16	450	68	7000	15	1.45E-05	1.30	0.26	1.96	68	59
2000000	16	450	68	7000	15	1.45E-05	1.30	0.26	1.96	68	59
2000000	16	450	68	7000	15	1.45E-05	1.30	0.26	1.96	68	58
2000000	16	450	70	7000	15	1.45E-05	1.30	0.26	1.96	70	56
2000000	16	450	72	7000	15	1.45E-05	1.30	0.26	1.96	72	55
2000000	16	450	73	7000	15	1.45E-05	1.30	0.26	1.96	73	54
2000000	16	450	76	7000	15	1.45E-05	1.30	0.26	1.96	76	53
2000000	16	450	76	7000	15	1.45E-05	1.30	0.26	1.96	76	53
2000000	16	450	82	7000	15	1.45E-05	1.30	0.26	1.96	82	53
2000000	16	450	83	7000	15	1.45E-05	1.30	0.26	1.96	83	53
2000000	16	450	86	7000	15	1.45E-05	1.30	0.26	1.96	86	53
2000000	16	450	86	7000	15	1.45E-05	1.30	0.26	1.96	86	53
2000000	16	450	89	7000	15	1.45E-05	1.30	0.26	1.96	89	53
2000000	16	450	89	7000	15	1.45E-05	1.30	0.26	1.96	89	53
2000000	16	450	91	7000	15	1.45E-05	1.30	0.26	1.96	91	53
2000000	16	450	92	7000	15	1.45E-05	1.30	0.26	1.96	92	53
2000000	16	450	93	7000	15	1.45E-05	1.30	0.26	1.96	93	53
2000000	16	450	94	7000	15	1.45E-05	1.30	0.26	1.96	94	53
2000000	16	450	99	7000	15	1.45E-05	1.30	0.26	1.96	99	53
2000000	16	450	99	7000	15	1.45E-05	1.30	0.26	1.96	99	53
2000000	16	450	102	7000	15	1.45E-05	1.30	0.26	1.96	102	53
2000000	16	450	103	7000	15	1.45E-05	1.30	0.26	1.96	103	53
2000000	16	450	107	7000	15	1.45E-05	1.30	0.26	1.96	107	53
2000000	16	450	107	7000	15	1.45E-05	1.30	0.26	1.96	107	53
2000000	16	450	109	7000	15	1.45E-05	1.30	0.26	1.96	109	53
2000000	16	450	109	7000	15	1.45E-05	1.30	0.26	1.96	109	53
2000000	16	450	111	7000	15	1.45E-05	1.30	0.26	1.96	111	53
2000000	16	450	112	7000	15	1.45E-05	1.30	0.26	1.96	112	53
2000000	16	450	113	7000	15	1.45E-05	1.30	0.26	1.96	113	53
2000000	16	450	114	7000	15	1.45E-05	1.30	0.26	1.96	114	53
2000000	16	450	117	7000	15	1.45E-05	1.30	0.26	1.96	117	53
2000000	16	450	120	7000	15	1.45E-05	1.30	0.26	1.96	120	53
2000000	16	450	121	7000	15	1.45E-05	1.30	0.26	1.96	121	53
2000000	16	450	123	7000	15	1.45E-05	1.30	0.26	1.96	123	53
2000000	16	450	124	7000	15	1.45E-05	1.30	0.26	1.96	124	53
2000000	16	450	125	7000	15	1.45E-05	1.30	0.26	1.96	125	53
2000000	16	450	127	7000	15	1.45E-05	1.30	0.26	1.96	127	52
2000000	16	450	127	7000	15	1.45E-05	1.30	0.26	1.96	127	52

Effect of Varying Dispersion Coefficient E with all other parameters held constant

2000000	16	450	127	7000	15	1.45E-05	1.30	0.26	1.96	127	52
2000000	16	450	128	7000	15	1.45E-05	1.30	0.26	1.96	128	52
2000000	16	450	130	7000	15	1.45E-05	1.30	0.26	1.96	130	52
2000000	16	450	134	7000	15	1.45E-05	1.30	0.26	1.96	134	52
2000000	16	450	135	7000	15	1.45E-05	1.30	0.26	1.96	135	52
2000000	16	450	136	7000	15	1.45E-05	1.30	0.26	1.96	136	52
2000000	16	450	139	7000	15	1.45E-05	1.30	0.26	1.96	139	52
2000000	16	450	139	7000	15	1.45E-05	1.30	0.26	1.96	139	52
2000000	16	450	142	7000	15	1.45E-05	1.30	0.26	1.96	142	52
2000000	16	450	148	7000	15	1.45E-05	1.30	0.26	1.96	148	52
2000000	16	450	148	7000	15	1.45E-05	1.30	0.26	1.96	148	52
2000000	16	450	149	7000	15	1.45E-05	1.30	0.26	1.96	149	52
2000000	16	450	149	7000	15	1.45E-05	1.30	0.26	1.96	149	52
2000000	16	450	149	7000	15	1.45E-05	1.30	0.26	1.96	149	52
2000000	16	450	150	7000	15	1.45E-05	1.30	0.26	1.96	150	52
2000000	16	450	152	7000	15	1.45E-05	1.30	0.26	1.96	152	52
2000000	16	450	155	7000	15	1.45E-05	1.30	0.26	1.96	155	52
2000000	16	450	157	7000	15	1.45E-05	1.30	0.26	1.96	157	52
2000000	16	450	163	7000	15	1.45E-05	1.30	0.26	1.96	163	52
2000000	16	450	164	7000	15	1.45E-05	1.30	0.26	1.96	164	52
2000000	16	450	165	7000	15	1.45E-05	1.30	0.26	1.96	165	52
2000000	16	450	166	7000	15	1.45E-05	1.30	0.26	1.96	166	52
2000000	16	450	169	7000	15	1.45E-05	1.30	0.26	1.96	169	52
2000000	16	450	171	7000	15	1.45E-05	1.30	0.26	1.96	171	52
2000000	16	450	172	7000	15	1.45E-05	1.30	0.26	1.96	172	52
2000000	16	450	173	7000	15	1.45E-05	1.30	0.26	1.96	173	52
2000000	16	450	173	7000	15	1.45E-05	1.30	0.26	1.96	173	52
2000000	16	450	176	7000	15	1.45E-05	1.30	0.26	1.96	176	52
2000000	16	450	177	7000	15	1.45E-05	1.30	0.26	1.96	177	52
2000000	16	450	178	7000	15	1.45E-05	1.30	0.26	1.96	178	52
2000000	16	450	179	7000	15	1.45E-05	1.30	0.26	1.96	179	52
2000000	16	450	181	7000	15	1.45E-05	1.30	0.26	1.96	181	52
2000000	16	450	182	7000	15	1.45E-05	1.30	0.26	1.96	182	52
2000000	16	450	184	7000	15	1.45E-05	1.30	0.26	1.96	184	52
2000000	16	450	184	7000	15	1.45E-05	1.30	0.26	1.96	184	52
2000000	16	450	185	7000	15	1.45E-05	1.30	0.26	1.96	185	52
2000000	16	450	185	7000	15	1.45E-05	1.30	0.26	1.96	185	52
2000000	16	450	186	7000	15	1.45E-05	1.30	0.26	1.96	186	52
2000000	16	450	188	7000	15	1.45E-05	1.30	0.26	1.96	188	52
2000000	16	450	190	7000	15	1.45E-05	1.30	0.26	1.96	190	52
2000000	16	450	191	7000	15	1.45E-05	1.30	0.26	1.96	191	52
2000000	16	450	194	7000	15	1.45E-05	1.30	0.26	1.96	194	52
2000000	16	450	197	7000	15	1.45E-05	1.30	0.26	1.96	197	52
2000000	16	450	197	7000	15	1.45E-05	1.30	0.26	1.96	197	52
2000000	16	450	197	7000	15	1.45E-05	1.30	0.26	1.96	197	52
2000000	16	450	198	7000	15	1.45E-05	1.30	0.26	1.96	198	52
2000000	16	450	198	7000	15	1.45E-05	1.30	0.26	1.96	198	52
2000000	16	450	198	7000	15	1.45E-05	1.30	0.26	1.96	198	52
2000000	16	450	199	7000	15	1.45E-05	1.30	0.26	1.96	199	52
2000000	16	450	199	7000	15	1.45E-05	1.30	0.26	1.96	199	52

Affect of Varying No with all other parameters held constant

No	u	x	E	Iavg	SS	a	b	c	m		N
51190	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	51190	53
118914	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	118914	53
122961	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	122961	53
155156	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	155156	53
155811	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	155811	53
170093	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	170093	53
204015	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	204015	53
222582	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	222582	53
231747	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	231747	53
237162	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	237162	53
248708	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	248708	53
255670	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	255670	53
268822	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	268822	53
307802	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	307802	53
416886	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	416886	53
444380	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	444380	53
476337	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	476337	53
503594	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	503594	53
507462	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	507462	53
511985	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	511985	53
512520	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	512520	53
520138	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	520138	53
544954	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	544954	53
558701	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	558701	53
569413	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	569413	53
575721	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	575721	53
578816	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	578816	53
587861	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	587861	53
599942	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	599942	53
611547	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	611547	53
635232	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	635232	53
637315	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	637315	53
639279	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	639279	53
649574	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	649574	53
680877	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	680877	53
687007	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	687007	53
688792	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	688792	53
727831	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	727831	53
731402	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	731402	53
732711	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	732711	53
797816	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	797816	53
801506	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	801506	53
811504	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	811504	53
811504	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	811504	53
815491	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	815491	53
818824	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	818824	53
836618	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	836618	53
897081	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	897081	53
906246	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	906246	53
932371	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	932371	53

Affect of Varying No with all other parameters held constant

951236	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	951236	53
957009	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	957009	53
965043	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	965043	53
980992	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	980992	53
1008426	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1008426	53
1025625	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1025625	53
1029196	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1029196	53
1065676	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1065676	53
1066747	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1066747	53
1068175	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1068175	53
1092753	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1092753	53
1097633	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1097633	53
1109893	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1109893	53
1151431	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1151431	53
1160775	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1160775	53
1170653	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1170653	53
1177378	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1177378	53
1189340	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1189340	53
1200528	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1200528	53
1208502	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1208502	53
1210288	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1210288	53
1215406	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1215406	53
1226594	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1226594	53
1253731	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1253731	53
1261348	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1261348	53
1273786	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1273786	53
1361565	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1361565	53
1377395	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1377395	53
1394237	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1394237	53
1423397	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1423397	53
1433752	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1433752	53
1441726	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1441726	53
1492489	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1492489	53
1500642	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1500642	53
1530636	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1530636	53
1555750	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1555750	53
1612761	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1612761	53
1635852	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1635852	53
1652336	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1652336	53
1656561	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1656561	53
1658109	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1658109	53
1671499	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1671499	53
1698041	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1698041	53
1717144	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1717144	53
1726428	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1726428	53
1741484	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1741484	53
1757314	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1757314	53
1867588	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1867588	53
1882287	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1882287	53
1897581	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	1897581	53

Affect of Varying Suspended Solids with all other parameters held constant

No	u	x	E	lavg	SS	a	b	c	m		N
2000000	16	450	75.00	7000	0	1.45E-05	1.30	0.26	1.96	0	1
2000000	16	450	75.00	7000	1	1.45E-05	1.30	0.26	1.96	1	1
2000000	16	450	75.00	7000	2	1.45E-05	1.30	0.26	1.96	2	2
2000000	16	450	75.00	7000	2	1.45E-05	1.30	0.26	1.96	2	2
2000000	16	450	75.00	7000	2	1.45E-05	1.30	0.26	1.96	2	2
2000000	16	450	75.00	7000	3	1.45E-05	1.30	0.26	1.96	3	3
2000000	16	450	75.00	7000	3	1.45E-05	1.30	0.26	1.96	3	4
2000000	16	450	75.00	7000	3	1.45E-05	1.30	0.26	1.96	3	4
2000000	16	450	75.00	7000	3	1.45E-05	1.30	0.26	1.96	3	4
2000000	16	450	75.00	7000	4	1.45E-05	1.30	0.26	1.96	4	5
2000000	16	450	75.00	7000	4	1.45E-05	1.30	0.26	1.96	4	5
2000000	16	450	75.00	7000	5	1.45E-05	1.30	0.26	1.96	5	7
2000000	16	450	75.00	7000	5	1.45E-05	1.30	0.26	1.96	5	7
2000000	16	450	75.00	7000	6	1.45E-05	1.30	0.26	1.96	6	10
2000000	16	450	75.00	7000	7	1.45E-05	1.30	0.26	1.96	7	14
2000000	16	450	75.00	7000	8	1.45E-05	1.30	0.26	1.96	8	17
2000000	16	450	75.00	7000	9	1.45E-05	1.30	0.26	1.96	9	22
2000000	16	450	75.00	7000	10	1.45E-05	1.30	0.26	1.96	10	23
2000000	16	450	75.00	7000	11	1.45E-05	1.30	0.26	1.96	11	28
2000000	16	450	75.00	7000	11	1.45E-05	1.30	0.26	1.96	11	30
2000000	16	450	75.00	7000	11	1.45E-05	1.30	0.26	1.96	11	32
2000000	16	450	75.00	7000	12	1.45E-05	1.30	0.26	1.96	12	32
2000000	16	450	75.00	7000	12	1.45E-05	1.30	0.26	1.96	12	37
2000000	16	450	75.00	7000	13	1.45E-05	1.30	0.26	1.96	13	38
2000000	16	450	75.00	7000	14	1.45E-05	1.30	0.26	1.96	14	44
2000000	16	450	75.00	7000	14	1.45E-05	1.30	0.26	1.96	14	50
2000000	16	450	75.00	7000	16	1.45E-05	1.30	0.26	1.96	16	61
2000000	16	450	75.00	7000	17	1.45E-05	1.30	0.26	1.96	17	69
2000000	16	450	75.00	7000	18	1.45E-05	1.30	0.26	1.96	18	76
2000000	16	450	75.00	7000	21	1.45E-05	1.30	0.26	1.96	21	98
2000000	16	450	75.00	7000	23	1.45E-05	1.30	0.26	1.96	23	121
2000000	16	450	75.00	7000	23	1.45E-05	1.30	0.26	1.96	23	125
2000000	16	450	75.00	7000	23	1.45E-05	1.30	0.26	1.96	23	125
2000000	16	450	75.00	7000	23	1.45E-05	1.30	0.26	1.96	23	126
2000000	16	450	75.00	7000	25	1.45E-05	1.30	0.26	1.96	25	139
2000000	16	450	75.00	7000	25	1.45E-05	1.30	0.26	1.96	25	141
2000000	16	450	75.00	7000	25	1.45E-05	1.30	0.26	1.96	25	143
2000000	16	450	75.00	7000	27	1.45E-05	1.30	0.26	1.96	27	165
2000000	16	450	75.00	7000	27	1.45E-05	1.30	0.26	1.96	27	165
2000000	16	450	75.00	7000	27	1.45E-05	1.30	0.26	1.96	27	166
2000000	16	450	75.00	7000	27	1.45E-05	1.30	0.26	1.96	27	170
2000000	16	450	75.00	7000	29	1.45E-05	1.30	0.26	1.96	29	186
2000000	16	450	75.00	7000	29	1.45E-05	1.30	0.26	1.96	29	190
2000000	16	450	75.00	7000	29	1.45E-05	1.30	0.26	1.96	29	193
2000000	16	450	75.00	7000	30	1.45E-05	1.30	0.26	1.96	30	206
2000000	16	450	75.00	7000	30	1.45E-05	1.30	0.26	1.96	30	209
2000000	16	450	75.00	7000	31	1.45E-05	1.30	0.26	1.96	31	224
2000000	16	450	75.00	7000	32	1.45E-05	1.30	0.26	1.96	32	231
2000000	16	450	75.00	7000	33	1.45E-05	1.30	0.26	1.96	33	244
2000000	16	450	75.00	7000	33	1.45E-05	1.30	0.26	1.96	33	247

Affect of Varying Suspended Solids with all other parameters held constant

2000000	16	450	75.00	7000	33	1.45E-05	1.30	0.26	1.96	33	250
2000000	16	450	75.00	7000	35	1.45E-05	1.30	0.26	1.96	35	272
2000000	16	450	75.00	7000	38	1.45E-05	1.30	0.26	1.96	38	322
2000000	16	450	75.00	7000	40	1.45E-05	1.30	0.26	1.96	40	351
2000000	16	450	75.00	7000	40	1.45E-05	1.30	0.26	1.96	40	364
2000000	16	450	75.00	7000	41	1.45E-05	1.30	0.26	1.96	41	373
2000000	16	450	75.00	7000	41	1.45E-05	1.30	0.26	1.96	41	380
2000000	16	450	75.00	7000	43	1.45E-05	1.30	0.26	1.96	43	409
2000000	16	450	75.00	7000	45	1.45E-05	1.30	0.26	1.96	45	456
2000000	16	450	75.00	7000	46	1.45E-05	1.30	0.26	1.96	46	464
2000000	16	450	75.00	7000	46	1.45E-05	1.30	0.26	1.96	46	474
2000000	16	450	75.00	7000	47	1.45E-05	1.30	0.26	1.96	47	499
2000000	16	450	75.00	7000	50	1.45E-05	1.30	0.26	1.96	50	555
2000000	16	450	75.00	7000	50	1.45E-05	1.30	0.26	1.96	50	561
2000000	16	450	75.00	7000	51	1.45E-05	1.30	0.26	1.96	51	574
2000000	16	450	75.00	7000	51	1.45E-05	1.30	0.26	1.96	51	574
2000000	16	450	75.00	7000	52	1.45E-05	1.30	0.26	1.96	52	593
2000000	16	450	75.00	7000	52	1.45E-05	1.30	0.26	1.96	52	596
2000000	16	450	75.00	7000	52	1.45E-05	1.30	0.26	1.96	52	610
2000000	16	450	75.00	7000	52	1.45E-05	1.30	0.26	1.96	52	611
2000000	16	450	75.00	7000	53	1.45E-05	1.30	0.26	1.96	53	632
2000000	16	450	75.00	7000	53	1.45E-05	1.30	0.26	1.96	53	635
2000000	16	450	75.00	7000	57	1.45E-05	1.30	0.26	1.96	57	718
2000000	16	450	75.00	7000	57	1.45E-05	1.30	0.26	1.96	57	729
2000000	16	450	75.00	7000	58	1.45E-05	1.30	0.26	1.96	58	735
2000000	16	450	75.00	7000	58	1.45E-05	1.30	0.26	1.96	58	748
2000000	16	450	75.00	7000	58	1.45E-05	1.30	0.26	1.96	58	752
2000000	16	450	75.00	7000	58	1.45E-05	1.30	0.26	1.96	58	755
2000000	16	450	75.00	7000	60	1.45E-05	1.30	0.26	1.96	60	788
2000000	16	450	75.00	7000	60	1.45E-05	1.30	0.26	1.96	60	803
2000000	16	450	75.00	7000	61	1.45E-05	1.30	0.26	1.96	61	818
2000000	16	450	75.00	7000	61	1.45E-05	1.30	0.26	1.96	61	821
2000000	16	450	75.00	7000	62	1.45E-05	1.30	0.26	1.96	62	837
2000000	16	450	75.00	7000	62	1.45E-05	1.30	0.26	1.96	62	838
2000000	16	450	75.00	7000	62	1.45E-05	1.30	0.26	1.96	62	854
2000000	16	450	75.00	7000	62	1.45E-05	1.30	0.26	1.96	62	862
2000000	16	450	75.00	7000	63	1.45E-05	1.30	0.26	1.96	63	881
2000000	16	450	75.00	7000	64	1.45E-05	1.30	0.26	1.96	64	897
2000000	16	450	75.00	7000	64	1.45E-05	1.30	0.26	1.96	64	899
2000000	16	450	75.00	7000	65	1.45E-05	1.30	0.26	1.96	65	917
2000000	16	450	75.00	7000	65	1.45E-05	1.30	0.26	1.96	65	939
2000000	16	450	75.00	7000	66	1.45E-05	1.30	0.26	1.96	66	947
2000000	16	450	75.00	7000	66	1.45E-05	1.30	0.26	1.96	66	971
2000000	16	450	75.00	7000	67	1.45E-05	1.30	0.26	1.96	67	999
2000000	16	450	75.00	7000	68	1.45E-05	1.30	0.26	1.96	68	1009
2000000	16	450	75.00	7000	68	1.45E-05	1.30	0.26	1.96	68	1013
2000000	16	450	75.00	7000	68	1.45E-05	1.30	0.26	1.96	68	1024
2000000	16	450	75.00	7000	69	1.45E-05	1.30	0.26	1.96	69	1054
2000000	16	450	75.00	7000	70	1.45E-05	1.30	0.26	1.96	70	1065
2000000	16	450	75.00	7000	70	1.45E-05	1.30	0.26	1.96	70	1072

Affect of Varying Velocity, u with all other parameters held constant

No	u	x	E	Iavg	SS	a	b	c	m		N
2000000	5	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	5	52
2000000	5	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	5	52
2000000	5	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	5	52
2000000	6	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	6	52
2000000	6	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	6	52
2000000	6	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	6	52
2000000	7	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	7	52
2000000	7	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	7	52
2000000	7	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	7	52
2000000	7	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	7	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	8	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	8	52
2000000	9	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	9	52
2000000	9	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	9	52
2000000	9	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	9	52
2000000	9	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	9	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	10	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	10	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	11	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	11	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	12	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	12	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52

Affect of Varying Velocity, u with all other parameters held constant

2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	13	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	13	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	52
2000000	14	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	14	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	15	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	15	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	53
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	54
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	54
2000000	16	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	16	55
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	58
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	63
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	74
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	74
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	78
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	86
2000000	17	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	17	105
2000000	18	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	18	252
2000000	18	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	18	262
2000000	18	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	18	377
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	2270
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	3447
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	5031
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	5248
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	18660
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	19152
2000000	19	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	19	20850
2000000	20	450	75.00	7000	15	1.45E-05	1.30	0.26	1.96	20	46178

Effect of Varying Reactor Length, x with all other parameters held constant

No	u	x	E	Iavg	SS	a	b	c	m		N
2000000	16	107	75.00	7000	15	1.45E-05	1.30	0.26	1.96	107	63083
2000000	16	122	75.00	7000	15	1.45E-05	1.30	0.26	1.96	122	39046
2000000	16	126	75.00	7000	15	1.45E-05	1.30	0.26	1.96	126	33733
2000000	16	140	75.00	7000	15	1.45E-05	1.30	0.26	1.96	140	21776
2000000	16	147	75.00	7000	15	1.45E-05	1.30	0.26	1.96	147	17422
2000000	16	153	75.00	7000	15	1.45E-05	1.30	0.26	1.96	153	14392
2000000	16	155	75.00	7000	15	1.45E-05	1.30	0.26	1.96	155	13397
2000000	16	190	75.00	7000	15	1.45E-05	1.30	0.26	1.96	190	4314
2000000	16	200	75.00	7000	15	1.45E-05	1.30	0.26	1.96	200	3151
2000000	16	210	75.00	7000	15	1.45E-05	1.30	0.26	1.96	210	2303
2000000	16	224	75.00	7000	15	1.45E-05	1.30	0.26	1.96	224	1488
2000000	16	226	75.00	7000	15	1.45E-05	1.30	0.26	1.96	226	1377
2000000	16	227	75.00	7000	15	1.45E-05	1.30	0.26	1.96	227	1347
2000000	16	232	75.00	7000	15	1.45E-05	1.30	0.26	1.96	232	1165
2000000	16	235	75.00	7000	15	1.45E-05	1.30	0.26	1.96	235	1045
2000000	16	236	75.00	7000	15	1.45E-05	1.30	0.26	1.96	236	1030
2000000	16	263	75.00	7000	15	1.45E-05	1.30	0.26	1.96	263	454
2000000	16	264	75.00	7000	15	1.45E-05	1.30	0.26	1.96	264	443
2000000	16	265	75.00	7000	15	1.45E-05	1.30	0.26	1.96	265	434
2000000	16	272	75.00	7000	15	1.45E-05	1.30	0.26	1.96	272	360
2000000	16	278	75.00	7000	15	1.45E-05	1.30	0.26	1.96	278	299
2000000	16	281	75.00	7000	15	1.45E-05	1.30	0.26	1.96	281	279
2000000	16	282	75.00	7000	15	1.45E-05	1.30	0.26	1.96	282	276
2000000	16	282	75.00	7000	15	1.45E-05	1.30	0.26	1.96	282	270
2000000	16	289	75.00	7000	15	1.45E-05	1.30	0.26	1.96	289	229
2000000	16	291	75.00	7000	15	1.45E-05	1.30	0.26	1.96	291	216
2000000	16	300	75.00	7000	15	1.45E-05	1.30	0.26	1.96	300	178
2000000	16	301	75.00	7000	15	1.45E-05	1.30	0.26	1.96	301	173
2000000	16	302	75.00	7000	15	1.45E-05	1.30	0.26	1.96	302	167
2000000	16	308	75.00	7000	15	1.45E-05	1.30	0.26	1.96	308	148
2000000	16	309	75.00	7000	15	1.45E-05	1.30	0.26	1.96	309	144
2000000	16	316	75.00	7000	15	1.45E-05	1.30	0.26	1.96	316	126
2000000	16	320	75.00	7000	15	1.45E-05	1.30	0.26	1.96	320	116
2000000	16	324	75.00	7000	15	1.45E-05	1.30	0.26	1.96	324	109
2000000	16	339	75.00	7000	15	1.45E-05	1.30	0.26	1.96	339	87
2000000	16	363	75.00	7000	15	1.45E-05	1.30	0.26	1.96	363	68
2000000	16	364	75.00	7000	15	1.45E-05	1.30	0.26	1.96	364	68
2000000	16	368	75.00	7000	15	1.45E-05	1.30	0.26	1.96	368	66
2000000	16	370	75.00	7000	15	1.45E-05	1.30	0.26	1.96	370	65
2000000	16	370	75.00	7000	15	1.45E-05	1.30	0.26	1.96	370	65
2000000	16	416	75.00	7000	15	1.45E-05	1.30	0.26	1.96	416	55
2000000	16	419	75.00	7000	15	1.45E-05	1.30	0.26	1.96	419	55
2000000	16	442	75.00	7000	15	1.45E-05	1.30	0.26	1.96	442	54
2000000	16	445	75.00	7000	15	1.45E-05	1.30	0.26	1.96	445	54
2000000	16	453	75.00	7000	15	1.45E-05	1.30	0.26	1.96	453	53
2000000	16	454	75.00	7000	15	1.45E-05	1.30	0.26	1.96	454	53
2000000	16	472	75.00	7000	15	1.45E-05	1.30	0.26	1.96	472	53
2000000	16	487	75.00	7000	15	1.45E-05	1.30	0.26	1.96	487	53
2000000	16	492	75.00	7000	15	1.45E-05	1.30	0.26	1.96	492	53
2000000	16	501	75.00	7000	15	1.45E-05	1.30	0.26	1.96	501	53

Effect of Varying Reactor Length, x with all other parameters held constant

2000000	16	507	75.00	7000	15	1.45E-05	1.30	0.26	1.96	507	53
2000000	16	516	75.00	7000	15	1.45E-05	1.30	0.26	1.96	516	53
2000000	16	519	75.00	7000	15	1.45E-05	1.30	0.26	1.96	519	53
2000000	16	538	75.00	7000	15	1.45E-05	1.30	0.26	1.96	538	53
2000000	16	542	75.00	7000	15	1.45E-05	1.30	0.26	1.96	542	53
2000000	16	546	75.00	7000	15	1.45E-05	1.30	0.26	1.96	546	53
2000000	16	549	75.00	7000	15	1.45E-05	1.30	0.26	1.96	549	53
2000000	16	603	75.00	7000	15	1.45E-05	1.30	0.26	1.96	603	53
2000000	16	625	75.00	7000	15	1.45E-05	1.30	0.26	1.96	625	52
2000000	16	663	75.00	7000	15	1.45E-05	1.30	0.26	1.96	663	52
2000000	16	669	75.00	7000	15	1.45E-05	1.30	0.26	1.96	669	52
2000000	16	678	75.00	7000	15	1.45E-05	1.30	0.26	1.96	678	52
2000000	16	679	75.00	7000	15	1.45E-05	1.30	0.26	1.96	679	52
2000000	16	710	75.00	7000	15	1.45E-05	1.30	0.26	1.96	710	52
2000000	16	715	75.00	7000	15	1.45E-05	1.30	0.26	1.96	715	52
2000000	16	731	75.00	7000	15	1.45E-05	1.30	0.26	1.96	731	52
2000000	16	731	75.00	7000	15	1.45E-05	1.30	0.26	1.96	731	52
2000000	16	736	75.00	7000	15	1.45E-05	1.30	0.26	1.96	736	52
2000000	16	741	75.00	7000	15	1.45E-05	1.30	0.26	1.96	741	52
2000000	16	743	75.00	7000	15	1.45E-05	1.30	0.26	1.96	743	52
2000000	16	763	75.00	7000	15	1.45E-05	1.30	0.26	1.96	763	52
2000000	16	767	75.00	7000	15	1.45E-05	1.30	0.26	1.96	767	52
2000000	16	779	75.00	7000	15	1.45E-05	1.30	0.26	1.96	779	52
2000000	16	786	75.00	7000	15	1.45E-05	1.30	0.26	1.96	786	52
2000000	16	799	75.00	7000	15	1.45E-05	1.30	0.26	1.96	799	52
2000000	16	802	75.00	7000	15	1.45E-05	1.30	0.26	1.96	802	52
2000000	16	805	75.00	7000	15	1.45E-05	1.30	0.26	1.96	805	52
2000000	16	813	75.00	7000	15	1.45E-05	1.30	0.26	1.96	813	52
2000000	16	828	75.00	7000	15	1.45E-05	1.30	0.26	1.96	828	52
2000000	16	836	75.00	7000	15	1.45E-05	1.30	0.26	1.96	836	52
2000000	16	839	75.00	7000	15	1.45E-05	1.30	0.26	1.96	839	52
2000000	16	851	75.00	7000	15	1.45E-05	1.30	0.26	1.96	851	52
2000000	16	871	75.00	7000	15	1.45E-05	1.30	0.26	1.96	871	52
2000000	16	872	75.00	7000	15	1.45E-05	1.30	0.26	1.96	872	52
2000000	16	872	75.00	7000	15	1.45E-05	1.30	0.26	1.96	872	52
2000000	16	877	75.00	7000	15	1.45E-05	1.30	0.26	1.96	877	52
2000000	16	888	75.00	7000	15	1.45E-05	1.30	0.26	1.96	888	52
2000000	16	890	75.00	7000	15	1.45E-05	1.30	0.26	1.96	890	52
2000000	16	891	75.00	7000	15	1.45E-05	1.30	0.26	1.96	891	52
2000000	16	901	75.00	7000	15	1.45E-05	1.30	0.26	1.96	901	52
2000000	16	904	75.00	7000	15	1.45E-05	1.30	0.26	1.96	904	52
2000000	16	905	75.00	7000	15	1.45E-05	1.30	0.26	1.96	905	52
2000000	16	928	75.00	7000	15	1.45E-05	1.30	0.26	1.96	928	52
2000000	16	929	75.00	7000	15	1.45E-05	1.30	0.26	1.96	929	52
2000000	16	935	75.00	7000	15	1.45E-05	1.30	0.26	1.96	935	52
2000000	16	940	75.00	7000	15	1.45E-05	1.30	0.26	1.96	940	52
2000000	16	953	75.00	7000	15	1.45E-05	1.30	0.26	1.96	953	52
2000000	16	953	75.00	7000	15	1.45E-05	1.30	0.26	1.96	953	52
2000000	16	954	75.00	7000	15	1.45E-05	1.30	0.26	1.96	954	52
2000000	16	963	75.00	7000	15	1.45E-05	1.30	0.26	1.96	963	52

Effect of Varying Iavg with all other parameters held constant

No	u	x	E	Iavg	SS	a	b	c	m		N
2000000	16	450	75.00	4041	15	1.45E-05	1.30	0.26	1.96	4041	131394238
2000000	16	450	75.00	4078	15	1.45E-05	1.30	0.26	1.96	4078	101496271
2000000	16	450	75.00	4172	15	1.45E-05	1.30	0.26	1.96	4172	52651312
2000000	16	450	75.00	4250	15	1.45E-05	1.30	0.26	1.96	4250	30675845
2000000	16	450	75.00	4251	15	1.45E-05	1.30	0.26	1.96	4251	30572780
2000000	16	450	75.00	4304	15	1.45E-05	1.30	0.26	1.96	4304	21201584
2000000	16	450	75.00	4366	15	1.45E-05	1.30	0.26	1.96	4366	13867838
2000000	16	450	75.00	4371	15	1.45E-05	1.30	0.26	1.96	4371	13413157
2000000	16	450	75.00	4388	15	1.45E-05	1.30	0.26	1.96	4388	11917368
2000000	16	450	75.00	4437	15	1.45E-05	1.30	0.26	1.96	4437	8548854
2000000	16	450	75.00	4479	15	1.45E-05	1.30	0.26	1.96	4479	6452226
2000000	16	450	75.00	4559	15	1.45E-05	1.30	0.26	1.96	4559	3746439
2000000	16	450	75.00	4577	15	1.45E-05	1.30	0.26	1.96	4577	3323450
2000000	16	450	75.00	4686	15	1.45E-05	1.30	0.26	1.96	4686	1604082
2000000	16	450	75.00	4845	15	1.45E-05	1.30	0.26	1.96	4845	557977
2000000	16	450	75.00	4938	15	1.45E-05	1.30	0.26	1.96	4938	303994
2000000	16	450	75.00	5065	15	1.45E-05	1.30	0.26	1.96	5065	132780
2000000	16	450	75.00	5093	15	1.45E-05	1.30	0.26	1.96	5093	111231
2000000	16	450	75.00	5227	15	1.45E-05	1.30	0.26	1.96	5227	46780
2000000	16	450	75.00	5273	15	1.45E-05	1.30	0.26	1.96	5273	34878
2000000	16	450	75.00	5305	15	1.45E-05	1.30	0.26	1.96	5305	28442
2000000	16	450	75.00	5317	15	1.45E-05	1.30	0.26	1.96	5317	26356
2000000	16	450	75.00	5415	15	1.45E-05	1.30	0.26	1.96	5415	14170
2000000	16	450	75.00	5442	15	1.45E-05	1.30	0.26	1.96	5442	11908
2000000	16	450	75.00	5555	15	1.45E-05	1.30	0.26	1.96	5555	5867
2000000	16	450	75.00	5654	15	1.45E-05	1.30	0.26	1.96	5654	3193
2000000	16	450	75.00	5840	15	1.45E-05	1.30	0.26	1.96	5840	1041
2000000	16	450	75.00	5959	15	1.45E-05	1.30	0.26	1.96	5959	527
2000000	16	450	75.00	6054	15	1.45E-05	1.30	0.26	1.96	6054	319
2000000	16	450	75.00	6351	15	1.45E-05	1.30	0.26	1.96	6351	97
2000000	16	450	75.00	6610	15	1.45E-05	1.30	0.26	1.96	6610	62
2000000	16	450	75.00	6660	15	1.45E-05	1.30	0.26	1.96	6660	60
2000000	16	450	75.00	6661	15	1.45E-05	1.30	0.26	1.96	6661	59
2000000	16	450	75.00	6673	15	1.45E-05	1.30	0.26	1.96	6673	59
2000000	16	450	75.00	6807	15	1.45E-05	1.30	0.26	1.96	6807	55
2000000	16	450	75.00	6827	15	1.45E-05	1.30	0.26	1.96	6827	55
2000000	16	450	75.00	6849	15	1.45E-05	1.30	0.26	1.96	6849	55
2000000	16	450	75.00	7067	15	1.45E-05	1.30	0.26	1.96	7067	53
2000000	16	450	75.00	7068	15	1.45E-05	1.30	0.26	1.96	7068	53
2000000	16	450	75.00	7079	15	1.45E-05	1.30	0.26	1.96	7079	53
2000000	16	450	75.00	7113	15	1.45E-05	1.30	0.26	1.96	7113	53
2000000	16	450	75.00	7258	15	1.45E-05	1.30	0.26	1.96	7258	53
2000000	16	450	75.00	7296	15	1.45E-05	1.30	0.26	1.96	7296	53
2000000	16	450	75.00	7320	15	1.45E-05	1.30	0.26	1.96	7320	53
2000000	16	450	75.00	7434	15	1.45E-05	1.30	0.26	1.96	7434	53
2000000	16	450	75.00	7464	15	1.45E-05	1.30	0.26	1.96	7464	53
2000000	16	450	75.00	7588	15	1.45E-05	1.30	0.26	1.96	7588	53
2000000	16	450	75.00	7640	15	1.45E-05	1.30	0.26	1.96	7640	53
2000000	16	450	75.00	7749	15	1.45E-05	1.30	0.26	1.96	7749	53
2000000	16	450	75.00	7772	15	1.45E-05	1.30	0.26	1.96	7772	53

Effect of Varying Iavg with all other parameters held constant

2000000	16	450	75.00	7797	15	1.45E-05	1.30	0.26	1.96	7797	53
2000000	16	450	75.00	7962	15	1.45E-05	1.30	0.26	1.96	7962	52
2000000	16	450	75.00	8319	15	1.45E-05	1.30	0.26	1.96	8319	52
2000000	16	450	75.00	8515	15	1.45E-05	1.30	0.26	1.96	8515	52
2000000	16	450	75.00	8601	15	1.45E-05	1.30	0.26	1.96	8601	52
2000000	16	450	75.00	8654	15	1.45E-05	1.30	0.26	1.96	8654	52
2000000	16	450	75.00	8698	15	1.45E-05	1.30	0.26	1.96	8698	52
2000000	16	450	75.00	8882	15	1.45E-05	1.30	0.26	1.96	8882	52
2000000	16	450	75.00	9162	15	1.45E-05	1.30	0.26	1.96	9162	52
2000000	16	450	75.00	9204	15	1.45E-05	1.30	0.26	1.96	9204	52
2000000	16	450	75.00	9261	15	1.45E-05	1.30	0.26	1.96	9261	52
2000000	16	450	75.00	9403	15	1.45E-05	1.30	0.26	1.96	9403	52
2000000	16	450	75.00	9706	15	1.45E-05	1.30	0.26	1.96	9706	52
2000000	16	450	75.00	9735	15	1.45E-05	1.30	0.26	1.96	9735	52
2000000	16	450	75.00	9802	15	1.45E-05	1.30	0.26	1.96	9802	52
2000000	16	450	75.00	9802	15	1.45E-05	1.30	0.26	1.96	9802	52
2000000	16	450	75.00	9904	15	1.45E-05	1.30	0.26	1.96	9904	52
2000000	16	450	75.00	9919	15	1.45E-05	1.30	0.26	1.96	9919	52
2000000	16	450	75.00	9986	15	1.45E-05	1.30	0.26	1.96	9986	52
2000000	16	450	75.00	9992	15	1.45E-05	1.30	0.26	1.96	9992	52
2000000	16	450	75.00	10095	15	1.45E-05	1.30	0.26	1.96	10095	52
2000000	16	450	75.00	10111	15	1.45E-05	1.30	0.26	1.96	10111	52
2000000	16	450	75.00	10508	15	1.45E-05	1.30	0.26	1.96	10508	52
2000000	16	450	75.00	10558	15	1.45E-05	1.30	0.26	1.96	10558	52
2000000	16	450	75.00	10587	15	1.45E-05	1.30	0.26	1.96	10587	52
2000000	16	450	75.00	10643	15	1.45E-05	1.30	0.26	1.96	10643	52
2000000	16	450	75.00	10661	15	1.45E-05	1.30	0.26	1.96	10661	52
2000000	16	450	75.00	10677	15	1.45E-05	1.30	0.26	1.96	10677	52
2000000	16	450	75.00	10826	15	1.45E-05	1.30	0.26	1.96	10826	52
2000000	16	450	75.00	10890	15	1.45E-05	1.30	0.26	1.96	10890	52
2000000	16	450	75.00	10954	15	1.45E-05	1.30	0.26	1.96	10954	52
2000000	16	450	75.00	10967	15	1.45E-05	1.30	0.26	1.96	10967	52
2000000	16	450	75.00	11038	15	1.45E-05	1.30	0.26	1.96	11038	52
2000000	16	450	75.00	11040	15	1.45E-05	1.30	0.26	1.96	11040	52
2000000	16	450	75.00	11112	15	1.45E-05	1.30	0.26	1.96	11112	52
2000000	16	450	75.00	11143	15	1.45E-05	1.30	0.26	1.96	11143	52
2000000	16	450	75.00	11225	15	1.45E-05	1.30	0.26	1.96	11225	52
2000000	16	450	75.00	11291	15	1.45E-05	1.30	0.26	1.96	11291	52
2000000	16	450	75.00	11301	15	1.45E-05	1.30	0.26	1.96	11301	52
2000000	16	450	75.00	11372	15	1.45E-05	1.30	0.26	1.96	11372	52
2000000	16	450	75.00	11464	15	1.45E-05	1.30	0.26	1.96	11464	52
2000000	16	450	75.00	11493	15	1.45E-05	1.30	0.26	1.96	11493	52
2000000	16	450	75.00	11590	15	1.45E-05	1.30	0.26	1.96	11590	52
2000000	16	450	75.00	11701	15	1.45E-05	1.30	0.26	1.96	11701	52
2000000	16	450	75.00	11741	15	1.45E-05	1.30	0.26	1.96	11741	52
2000000	16	450	75.00	11758	15	1.45E-05	1.30	0.26	1.96	11758	52
2000000	16	450	75.00	11802	15	1.45E-05	1.30	0.26	1.96	11802	52
2000000	16	450	75.00	11916	15	1.45E-05	1.30	0.26	1.96	11916	52
2000000	16	450	75.00	11958	15	1.45E-05	1.30	0.26	1.96	11958	52
2000000	16	450	75.00	11985	15	1.45E-05	1.30	0.26	1.96	11985	52

Ozone Disinfection Efficiency Model Equation Manipulations

T	TCOD	N	Total Coliforms
1.00	0	4.38	23988.33
5.00	0	1.178717	15.09
10.00	0	-0.2	0.63
15.00	0	-1.0065	0.10
20.00	0	-1.57872	0.03
25.00	0	-2.02257	0.01
30.00	0	-2.38522	0.00
35.00	0	-2.69183	0.00
40.00	0	-2.95743	0.00
1.00	10	4.78	60255.96
5.00	10	1.578717	37.91
10.00	10	0.2	1.58
15.00	10	-0.6065	0.25
20.00	10	-1.17872	0.07
25.00	10	-1.62257	0.02
30.00	10	-1.98522	0.01
35.00	10	-2.29183	0.01
40.00	10	-2.55743	0.00
1.00	20	5.18	151356.12
5.00	20	1.978717	95.22
10.00	20	0.6	3.98
15.00	20	-0.2065	0.62
20.00	20	-0.77872	0.17
25.00	20	-1.22257	0.06
30.00	20	-1.58522	0.03
35.00	20	-1.89183	0.01
40.00	20	-2.15743	0.01
1.00	30	5.58	380189.40
5.00	30	2.378717	239.18
10.00	30	1	10.00
15.00	30	0.193502	1.56
20.00	30	-0.37872	0.42
25.00	30	-0.82257	0.15
30.00	30	-1.18522	0.07
35.00	30	-1.49183	0.03
40.00	30	-1.75743	0.02
1.00	40	5.98	954992.59
5.00	40	2.778717	600.78
10.00	40	1.4	25.12
15.00	40	0.593502	3.92
20.00	40	0.021283	1.05
25.00	40	-0.42257	0.38
30.00	40	-0.78522	0.16
35.00	40	-1.09183	0.08
40.00	40	-1.35743	0.04
1.00	50	6.38	2398832.92
5.00	50	3.178717	1509.10
10.00	50	1.8	63.10
15.00	50	0.993502	9.85
20.00	50	0.421283	2.64

25.00	50	-0.02257	0.95
30.00	50	-0.38522	0.41
35.00	50	-0.69183	0.20
40.00	50	-0.95743	0.11
1.00	60	6.78	6025595.86
5.00	60	3.578717	3790.68
10.00	60	2.2	158.49
15.00	60	1.393502	24.75
20.00	60	0.821283	6.63
25.00	60	0.377435	2.38
30.00	60	0.014785	1.03
35.00	60	-0.29183	0.51
40.00	60	-0.55743	0.28
1.00	70	7.18	15135612.48
5.00	70	3.978717	9521.76
10.00	70	2.6	398.11
15.00	70	1.793502	62.16
20.00	70	1.221283	16.64
25.00	70	0.777435	5.99
30.00	70	0.414785	2.60
35.00	70	0.108168	1.28
40.00	70	-0.15743	0.70
1.00	80	7.58	38018939.63
5.00	80	4.378717	23917.59
10.00	80	3	1000.00
15.00	80	2.193502	156.14
20.00	80	1.621283	41.81
25.00	80	1.177435	15.05
30.00	80	0.814785	6.53
35.00	80	0.508168	3.22
40.00	80	0.242565	1.75
1.00	90	7.98	95499258.60
5.00	90	4.778717	60078.26
10.00	90	3.4	2511.89
15.00	90	2.593502	392.19
20.00	90	2.021283	105.02
25.00	90	1.577435	37.80
30.00	90	1.214785	16.40
35.00	90	0.908168	8.09
40.00	90	0.642565	4.39
1.00	100	8.38	239883291.90
5.00	100	5.178717	150909.78
10.00	100	3.8	6309.57
15.00	100	2.993502	985.15
20.00	100	2.421283	263.80
25.00	100	1.977435	94.94
30.00	100	1.614785	41.19
35.00	100	1.308168	20.33
40.00	100	1.042565	11.03

Appendix C: Cost Data for Disinfection Alternatives

This appendix provides information and cost data obtained from vendors in the wastewater disinfection industry. This data is provided for information purposes only and should not be considered an official quote.

Ultraviolet Disinfection Systems

Three vendors were contacted with respect to UV disinfection systems: Trojan Technologies Inc., Fisher & Porter Co., and Infilco Degremont Inc. Trojan and Fisher & Porter each utilize the horizontal type system; while Infilco uses the vertical lamp system, as was seen at the Fairborn, Ohio WWTP. Infilco and Trojan have recently developed Package systems that have a horizontal lamp configuration that are simply piped into the effluent system and are not required to be placed in a contact basin. These package systems appear to be very feasible for the small type plant and require little construction cost. All the vendors contacted have the ability to custom design a system for a particular plant. The capital cost presented for the UV system includes all necessary components to operate the system.

Ozone Disinfection Systems

Ozonia North America of Lodi, New Jersey was contacted with respect to Ozone disinfection systems. The cost data for operation of an Ozone system was provided considering a one million gallon per day WWTP.

The capital cost presented for ozone is for the ozone generator only, the total does not include costs for equipment such as: a desiccant dryer, ozone off-gas destruct unit, contact basin, cryogenic or oxygen storage facility. A more accurate estimate of capital cost was not available from any supplier of ozone equipment.

Chlorination/Dechlorination Systems

SSgt Whippler, Operator, March AFB, CA, provided data for a chlorination system. The equipment cost specified below is for the control system and does not include the costs for the chlorine storage facility or cylinder handling system. The cost per pound of chlorine has risen from approximately $0.70/lb to $2-$3.00/lb.

Ecometrics Inc. was contacted for information on sulfur dioxide dechlorination equipment. The equipment cost listed below includes the following items: automatic servo meter, automatic chlorine residual analyzer, injector assembly, and feed controller. The system can be configured to operate on flow and/or residual readings. Pilot studies should be accomplished to determine the correct equipment required for the treatment facility.

Table 8. Cost Data for Alternative Disinfection Systems

	Chlorine	Dechlorination	UV	Ozone
Equipment Cost $	5,000	5,600	34,400	16,350
O&M Cost $	100 man-hours /year	Comparable to Chlorination	1,511	Unknown
$/lb of ..	≈ 2.50	≈ $0.70	N/A	0.70** (produced)
$/kW Hour	Unknown	Unknown	Unknown	0.06
$/ft^3 of O_2	N/A	N/A	N/A	0.30/100 ft^3

* Based on a 1.0 MGD WWTP.
** Does not include cost for supply oxygen.

The reader is reminded that the costs presented here are only estimates and if more precise numbers are required, the manufacturers or the Engineering Record Review should be consulted.

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Vita

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13. ABSTRACT (Maximum 200 words)

This study investigated the alternative methods of wastewater disinfection. Areas of interest included methods of operation, ease of maintenance, and effectiveness for various types of wastewater. A literature search revealed three major disinfection options, which include: chlorination/dechlorination, ultraviolet light, and ozone. A questionnaire was sent to the active duty Air Force installations that operate wastewater treatment plants, requesting permit limitations and monthly averages for a variety of wastewater parameters. The majority of Air Force wastewater treatment plants use chlorine for disinfection. Using data obtained form the questionnaire responses and established wastewater parameters from other research, the basic design model equations were manipulated. The results showed that ultraviolet and ozone disinfection are safe alternatives to chlorine, however, ultraviolet systems appear to be better suited for the size and type of wastewater treatment plant that is typical of an Air Force installation.

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